NsG-233-62

SUI 63-29

UNPUBLISHED PRELIMINARY DATA NASA CR 51070

[redacted]

64 p.

FACILITY FORM 602

| | |
|---|---|
| N65 17064 | |
| (ACCESSION NUMBER) | (THRU) |
| 64 | 1 |
| (PAGES) | (CODE) |
| CR 51070 | 29 |
| (NASA CR OR TMX OR AD NUMBER) | (CATEGORY) |

GPO PRICE $ ______

OTS PRICE(S) $ ______

Hard copy (HC) 3.00

Microfiche (MF) .75


Department of Physics and Astronomy

STATE UNIVERSITY OF IOWA

Iowa City, Iowa

(NASA CR-51070) SUI-63-29

A Survey of Magnetospheric Boundary Phenomena*

by


L. A. Frank and J. A. Van Allen aug 1963


58 refs

conf

To be presented at the Symposium on Results of the IGY-IGC, ~~University of California~~, Los Angeles.

August, 1963


Department of Physics and Astronomy
State University of Iowa
Iowa City, Iowa State U.) 4658001



*Supported in part by the National Aeronautics and Space Administration Research Grant NsG-233-62.)


(NASA

[redacted]

TABLE OF CONTENTS


| Chapter | | Page |
|---|---|---|
| Abstract | .......................................... | 1 |
| I. | Introduction .................................... | 2 |
| II. | Comparison of the Trajectories of Several Space Probes and Earth Satellites .............. | 4 |
| III. | Surveys of Low Energy Particles in the Vicinity of the Magnetospheric Boundary ........ | 6 |
| IV. | Surveys of Energetic Charged Particles in the Vicinity of the Magnetospheric Boundary .... | 10 |
| V. | Low Altitude High Latitude Studies ............. | 14 |
| VI. | Gross Character of Magnetic Fields Near the Magnetospheric Boundary ........................ | 16 |
| VII. | The Role of Polarization Electric Fields in Charged Particle Dynamics of the Magnetosphere .. | 19 |
| VIII. | Shocks, Deformation, and Motion of the Magnetospheric Boundary ........................ | 22 |
| IX. | Remark on the Dawn-Evening Distribution of Energetic Electrons in the Geomagnetic Equatorial Plane ............................ | 25 |
| X. | Summary ....................................... | 27 |
| Bibliography | ...................................... | 31 |
| Figure Captions | .................................. | 37 |

## ABSTRACT

15398

Our concept of the relationship between the outer limits of the geomagnetic field and the interplanetary medium has rapidly developed over the past few years due to critical experimental and theoretical examinations of these regions. The flow of solar plasma around the earth profoundly affects the phenomena of the distant magnetosphere; these phenomena in turn may be intimately related to processes occurring near the earth's surface via the geomagnetic lines of force. The highlights of our rapidly expanding knowledge of the phenomena in the vicinity of the interaction between the solar wind and the distant geomagnetic field are reviewed.

## I. INTRODUCTION

With the recent advent of satellites and space probes marked progress has occurred with respect to our knowledge, both experimental and theoretical, concerning the interaction of the earth's magnetic field and the solar wind. This interaction is believed to be closely associated with a variety of geophysical phenomena such as aurorae, magnetic storms, and ionospheric disturbances [cf. Chapman and Ferraro, 1931-1933; Akasofu and Chapman, 1961; Vestine, 1963; Axford and Hines, 1961]. The experimental results gathered over the past few years gives to us a gross model of an interplanetary plasma streaming radially and irregularly outward from the sun [Parker, 1958; Neugebauer and Snyder, 1962], compressing the earth's magnetic field on the sunward side and extending it on the night side [Chapman and Ferraro, 1931-33; Johnson, 1960; Beard, 1960]. Evidence [Freeman, 1963] exists that indicates a shock [Kellogg, 1962] is formed at the sunward boundary of the magnetosphere due to the supersonic flow of the plasma past the earth's distorted magnetosphere. Marked spatial asymmetries of charged particle distributions within and near the magnetospheric boundary [Frank, Van Allen, and Macagno, 1963] in the geomagnetic equatorial plane with respect to the earth-sun line have been observed and may be intimately associated with the flow of solar plasma in the vicinity of the earth. The experimental studies of the geomagnetic field in these distant regions of the magnetosphere have revealed large departures from an unperturbed dipolar field [Cahill and Amazeen, 1963; Heppner, Ness, Scearce, and Skillman, 1963; Coleman, Sonett, Judge, and Smith, 1960]. Although the present discussion emphasizes phenomena at large distances in the geomagnetic equatorial plane, the intimate relationship with low altitude, high latitude geophysical phenomena via the geomagnetic lines of force is of crucial importance in the interpretation of experimental results obtained in the vicinity of the magnetospheric boundary.

Our purpose in the present discussion will be directed toward summarizing our present knowledge concerning the immediate region of this interaction in the vicinity of the boundary of the earth's magnetosphere. Our intention is not to present a historical review or to provide a comprehensive bibliography (adequate references are provided in the literature cited herein); but we shall review the highlights of the experimental and theoretical results as a more or less integrated body of information.

## II. COMPARISON OF THE TRAJECTORIES OF SEVERAL SPACE PROBES AND EARTH SATELLITES

The azimuthal asymmetry of the charged particle distributions and of the character of the magnetic fields in the geomagnetic equatorial plane with respect to the earth-sun line beyond approximately 7 $R_E$ is of resounding importance to the interpretation of experimental results. It is worthwhile to review the locations with respect to the earth-sun line of those earth satellites and space probes which have donated heavily to our body of experimental information in these regions. In Figure 1 are displayed the projections of the trajectories of several of these probes onto the geomagnetic equatorial plane. It is immediately seen that Pioneers III and IV and Explorers XII and XIV scanned the dawn side of the magnetosphere while Lunik II and Explorers VI, X, and XIV have surveyed the nightside. Indeed, it should be apparent that Explorer XIV due to its long lifetime (2 October 1962 to present, July 1963) and apogee of a little more than 100,000 km has surveyed such a large portion of the geomagnetic equatorial plane that it may effectively be used as an important integrating factor in interpretation of the data of the remaining experiments. The local times at 100,000 km for Lunik I (2 January 1959), Pioneer V (11 March to 26 June 1960), and Pioneer I (11-12 October 1958) [not shown in Figure 1] were approximately 0800, 1500, and 1200, respectively [Smith, 1963]. Of the probes and satellites shown in Figure 1, all but Explorer X were within approximately 10° of the equatorial plane for the portions of the trajectories of interest here. The geomagnetic latitude of the Explorer X trajectory was approximately 45°.

## III. SURVEYS OF LOW ENERGY PARTICLES IN THE VICINITY OF THE MAGNETOSPHERIC BOUNDARY

Explorers X and XII and Lunik II have obtained some of the more important measurements of low energy particles near the fringes of the magnetosphere. These results are depicted graphically in Figure 2. As was mentioned previously, the geomagnetic latitude of Explorer X was approximately 45°; the Explorer X data [Bridge, Dilworth, Lazarus, Lyon, Rossi, and Scherb, 1962] given in Figure 2 have been extrapolated into the geomagnetic equatorial plane by the assumption of cylindrical symmetry about the earth-sun axis in order to obtain the approximate shape of the magnetosphere on the evening side of the earth-sun line. The intermittent observation of a plasma and of simultaneous changes in the character of the magnetic field beyond 22 $R_E$ on the night side of the earth has been interpreted by the experimenters [Bonetti, Bridge, Lazarus, Rossi, and Scherb, 1963; Heppner, Ness, Scearce, and Skillman, 1963] as the result of the boundary of the magnetospheric tail sweeping intermittently across the trajectory of the Explorer X probe. Bridge and his collaborators [1962] report the measurement of a plasma consisting of protons of approximately 500 eV in energy and fluxes of the order of $10^7$-$10^9$ $(cm^2\ sec)^{-1}$ just outside the tail of the magnetosphere and an upper limit of $5 \times 10^6$ $(cm^2\ sec)^{-1}$ when the instrumentation was within the tail. The measurements of Bridge et al. are in quantitative agreement with the interplanetary measurements with the Venus probe Mariner II [Neugebauer and Snyder, 1962]. Gringauz, Kurt, Moroz, and Shklovskii [1961] have measured an intense flux of low energy electrons in the radial distance range of 61,400 to 81,400 km with plasma cups on Lunik II at a sun-earth-probe angle ($L_{SEP}$, for brevity) of approximately 125° to the east [cf. Freeman, Van Allen, and Cahill, 1963] of the earth-sun line. These electrons were characterized by an average energy of 200 eV or greater and a flux of approximately $10^8$ $(cm^2\ sec)^{-1}$. This measurement apparently remained unique among the various low energy charged-particle measurements until Freeman [1963] reported a large flux of low energy electrons at $L_{SEP} \gtrsim 120°$ to the west of the earth-sun line with CdS total energy detectors (one with and one without a deflecting collimator magnet) on Explorer XII. These Explorer XII measurements indicated a flux of $\sim 10^8$ to $10^9$ $(cm^2\ sec)^{-1}$ if electrons of an average energy of 10 keV per electron were assumed. With plasma cups on Mars I (launch, 1 November 1962; local time at 15,000 km, ~ 2100; geomagnetic latitude at 15,000 km, ~ 50°) Gringauz and his collaborators [1963] again measured an electron flux of approximately the same magnitude and energy as with Lunik II but over a radial distance range of 8,500 km to 17,000 km, closer to the earth presumably due to the higher geomagnetic latitude of the trajectory. From the summary of the Lunik II and Explorer XII results in Figure 2, it is evident that large fluxes of low energy electrons exist on the night side of the earth and that further experiments with low energy electron (and proton) detectors are needed in order to complete this survey.

On the sunward side of the magnetosphere just beyond the magnetospheric boundary as delineated by the limit of durable trapping in the geomagnetic field of energetic electrons ($E \geq 40$ keV) and by the coincident observation of the discontinuity (termination) in the geomagnetic field beyond about 10 $R_E$, a persistent layer of electrons of energy flux ~ 30 ergs $(cm^2 \text{ sterad sec})^{-1}$ and of approximately 15,000 km in radial depth has been measured [Freeman, 1963]. These fluxes were observed until the apogee of Explorer XII had drifted to the dawn side of the earth where the apogee distance of 84,000 km was no longer sufficient to penetrate the magnetospheric boundary (see Figure 2). The possible relationship of these electron fluxes with regard to the present theory of shocks and transition regions is discussed later. The characteristics of the solar wind in interplanetary space distant from the influence of the earth's magnetosphere have recently been measured with the Venus probe Mariner II [Neugebauer and Snyder, 1962]. Typical values recorded were (protons only were measured):

$$v_o \simeq 500\text{-}800 \text{ km/sec (bulk velocity)}$$
$$n \simeq 2.5 \text{ (cm)}^{-3}$$
$$T \simeq 2\text{-}8 \times 10^5 \text{ °K}$$

and a fluctuating weak interplanetary magnetic field [Coleman, Davis, Smith, and Sonett, 1962]

$$B \simeq 5\gamma .$$

These data are indicative of a supersonic plasma flow past the earth since the Alfvén Mach number

$$M_A = v_o / v_A = \frac{(4\pi m_p n)^{1/2} v_o}{B} \sim 7 .$$

A rough estimate of $\sim 2\ (\mathrm{cm})^{-3}$ for the number density of electrons may be obtained by assuming that the ionized solar plasma is macroscopically neutral; the experimental difficulties of measuring electrons of energy $\sim \frac{1}{2} m_e v_o^2$ ( $\sim 1$ eV) are overwhelming. (The thermal energy of the electrons is $\sim 100$ eV if equipartition of energy between protons and electrons is invoked.)

## IV. SURVEYS OF ENERGETIC CHARGED PARTICLES IN THE VICINITY OF THE MAGNETOSPHERIC BOUNDARY

Electrons of energy greater than 250 keV which characterize the outer radiation zone are apparently not found in the vicinity of the magnetospheric boundary. Indeed, it has been shown recently that fluxes of electrons of energy less than 250 keV dominate these regions [Frank, Van Allen, and Macagno, 1963]. The fact that some of the high energy detectors (for example the heavily-shielded Geiger-Mueller tubes on Pioneers III and IV) have recorded significant responses in this region is now attributed to the inefficient intermediate process of bremsstrahlung production in the walls of the instruments by large fluxes of low energy electrons [cf. Frank, Van Allen, Whelpley, and Craven, 1963]. An apparent experimentally anamolous result existed in the determination of the radial extent of the geomagnetically trapped radiation as determined by similar heavily shielded Geiger-Mueller tubes (Anton 302's) on Pioneers III and IV [Van Allen and Frank, 1959 a, b] and Explorer VI [Arnoldy, Hoffman, and Winckler, 1960; Hoffman, Arnoldy, and Winckler, 1962] which returned to galactic background rates (and hence implied the limit of geomagnetic trapping) at radial distances of approximately 65,000, 90,000, and 45,000 km, respectively. Although these data were acquired during periods of differing geomagnetic activity, the large variation in radial extent of significant response over galactic background rates may be attributed in large part to their different trajectory directions with respect to the earth-sun line. Comparison of these data with the recent results of Explorers XII and XIV in Figures 3, 4, and 5 confirms the importance of this azimuthal asymmetry of low energy electrons in interpreting particle flux measurements beyond 7 $R_E$. In Figure 3 are shown the 302 counting rate contours as a function of radial distance for Pioneer III and Explorer XII for similar trajectories with respect to geomagnetic latitude and local time (see also Figure 1); in Figure 4 are displayed the contours for Pioneer IV and Explorer XIV again with similar trajectories with respect to geomagnetic latitude and local time; and in Figure 5 are displayed the corresponding data for Explorers VI and XIV. Lunik I (Mechta) charged particle measurements /Vernov, Chudakov, Valukov, Logachev, and Nikolaev, 1961/ yielded a result similar to that of Figure 4. The agreement among the various experimental results is thus quite remarkable when viewed with reference to a local time coordinate system. The higher count rates of Pioneer IV as compared to those of Explorer XIV in Figure 4 may be attributed to large solar and geomagnetic activity preceding the Pioneer IV flight /Van Allen and Frank, 1959 b/. By inspection this body of results indicates a relative dearth of electrons ($E \gtrsim 50$ keV) on the night side of the earth with respect to similar radial distances toward the sunward side of the magnetosphere.

The results of a comprehensive study /Frank, Van Allen, and Macagno, 1963/ of the spatial distribution of electrons of energy $E \gtrsim 40$ keV on the dawn side of the earth-sun line to geocentric radial distances of 105,000 km in the geomagnetic equatorial plane with thin-windowed (1.2 mg/cm$^2$ mica) G.M. tubes on Explorers XII and XIV are summarized in Figure 6. Salient characteristics of this survey of omnidirectional electron fluxes are:

(1) A general lack of electrons beyond 8 $R_E$ on the night side of the earth.

(2) A large "flaring" of the electron fluxes (typically $10^5$ to $10^6$ (cm$^2$ sec)$^{-1}$) at dawn and extending beyond the satellite apogee of 105,000 km.

(3) A sharp boundary or termination of these electron fluxes on the sunward side of the earth at approximately 10 $R_E$.

It should be remarked here that during magnetically disturbed periods the "average" contours presented in Figure 6 are apparently greatly distorted and that the evening contours have been extended from the dawn side by the assumption of symmetry about the earth-sun line. This symmetry will be discussed further in more detail in Section IX. Protons of energy greater than 100 keV have been measured with a scintillation detector on Explorer XII /Davis and Williamson, 1962/ and on Explorer XIV /Davis, 1963/ in these regions; no azimuthal studies of the proton intensities at large radial distances have been reported.

The Mars I space probe data [Vakulov, Vernov, Gorchakov, Logachev, A. Charakhchyan, T. Charakhchyan, and Chudakov, 1963] show that the geocentric radial termination of the flux of 70-80 keV electrons as measured on the night side of the earth ( $\sim$ 2100 local time) and at a geomagnetic latitude of $\sim 50°$ was at 15,000 km; it is of significant interest to compare this high latitude measurement with the termination of electron fluxes on the night side of the earth as shown in Figure 6. Just outside the magnetospheric boundary the Explorer XIV upper limits for the electron ($E_e \gtrsim 40$ keV) and proton ($E_p \gtrsim 500$ keV) fluxes are $5 \times 10^2$ $(cm^2\ sec)^{-1}$ [Frank, Van Allen, Whelpley, and Craven, 1963]. Measurements on Mariner II with a similar G.M. detector yield [Van Allen and Frank, 1962] an upper limit of $5 \times 10^1/(cm^2\ sec)^{-1}$ for the sum of proton and electron fluxes of the above energy ranges. These measurements imply that the large fluxes of energetic electrons found within the magnetosphere (see Figure 6) are not contributed directly by an efflux from the sun without subsequent acceleration in the vicinity of the magnetosphere.

## V. LOW ALTITUDE HIGH LATITUDE STUDIES

The intimate association of low altitude high latitude phenomena with processes occurring at large radial distances in the geomagnetic equatorial plane via geomagnetic lines of force certainly cannot be neglected. Discussion of related upper-atmospheric physical phenomena and surface magnetic field measurements is not within the realm of the text given here, but interesting surveys are given in Axford and Hines [1961] and Vestine [1963], for example. There has been one notable and interesting preliminary survey [O'Brien, 1963] of the high latitude distribution of trapped electrons ($E \gtrsim 40$ keV) with an Explorer XIV-type G.M. tube flown on Injun I in a nearly circular orbit of 1,000 km altitude with an inclination of 67°. This survey of trapped electrons revealed the large diurnal effect (shown in Figure 7) in the limit of the observation of trapped electrons as a function of invariant latitude $\Lambda$ ($\Lambda = \cos^{-1} (L)^{-1/2}$). (For definition of the B-L coordinate system, see McIlwain [1961].) The termination of trapped particle fluxes at local day was at $L \sim 16$ and at local night was at $L \sim 8$ as displayed by the corresponding limits of the loci of points indicated in Figure 7 by the solid and broken lines, respectively. The above low altitude measurements and the equatorial plane surveys of charged particle distributions

(Figures 2 and 6) were used to construct the meridianal section of the magnetosphere which is displayed in Figure 8. Studies of the latitude distributions of trapped and dumped electrons at evening and dawn are also of apparent interest. Important information obviously may be inferred about the dynamics and energy requirements of the outer magnetospheric system by these low altitude measurements.

## VI. GROSS CHARACTER OF MAGNETIC FIELDS NEAR THE MAGNETOSPHERIC BOUNDARY

The dynamical behavior of charged particles in the vicinity of the magnetospheric boundary is closely interlocked with the properties of the magnetic fields in these regions. The gross character of these magnetic fields /cf. Smith, 1963; Sonett, 1963; Heppner, Ness, Scearce, and Skillman, 1963; Cahill and Amazeen, 1963/ has been surveyed in part by Explorers X, XII, and XIV. Figure 9 displays charged particle and magnetic field measurements as Explorer XII passes inward through the magnetospheric boundary at local noon on 13 September 1961 /Freeman, Van Allen, and Cahill, 1963/; there were indications of solar activity a few days previous to and a sudden commencement at 1556 U.T. on 13 September. The experimenters have interpreted these measurements as follows:

(1) The discontinuity in direction, magnitude and general character of the magnetic field at 52,000 km determines the radial extent of the earth's magnetosphere.

(2) The observed limit of durable trapping of 40 keV electrons (SpL-SpB of Figure 9) corresponds closely to the discontinuity in the magnetic field.

(3) The magnetic field just inside the boundary has been compressed by a thermalized plasma of electrons (50 ergs $(cm^2 \text{ ster sec})^{-1}$) approximately 20,000 km thick located just outside of the boundary; the magnetic field just inside the boundary is approximately a factor of 2 larger than the value computed from Finch and Leaton

coefficients and is highly disordered outside the boundary.

(4) A betatron acceleration may have produced an enhancement of charged particle energy within the magnetosphere near the magnetospheric boundary.

These general characteristics of the sunward magnetospheric boundary are typical, although often somewhat attenuated since there were noticeably disturbed conditions at the boundary in the above cited case, of the Explorer XII measurements in these regions [cf. Cahill and Amazeen, 1962]. The results of the magnetic field measurements with Pioneers I [Sonett, Smith, and Sims, 1960] and V [Coleman, Sonett, Judge, and Smith, 1960] which also crossed the sunward side of the magnetospheric boundary were similar in character to those of Explorer XII. A graphical survey of these results [Bonetti, Bridge, Lazarus, Rossi, and Scherb, 1963] is given in Figure 10. The disordered magnetic fields of several $R_E$ in radial depth measured by each of these probes and satellites have been interpreted by various experimenters as characteristic of a transition region between a shock wave and the magnetospheric boundary. The generation of hydromagnetic waves in this region and the propagation of these waves within the magnetosphere have been considered [cf. Dessler, 1958, 1961; Dessler and Parker, 1959; Coleman and Sonett, 1961; MacDonald, 1961; Sonett, 1963]. Recent Explorer XIV magnetic field data [Cahill, 1963] to radial distances of approximately 100,000 km on the dawn side of the earth near the geomagnetic equatorial plane (also note Figure 6 at a similar spatial position) reveal no such discontinuity in the magnetic field as was observed on the sunward side of the earth. Consideration of these magnetic field measurements is mandatory in any interpretation of the asymmetric electron distributions of Figure 6 (for example, whether or not these electrons are trapped within the geomagnetic field). Explorer X magnetometer data [Heppner, Ness, Scearce, and Skillman, 1963] at distances beyond 22 $R_E$ toward the night side of earth have been interpreted by the experimenters as implying a magnetic field directed radially toward the night side and away from the sun within the magnetospheric tail and a disordered magnetic field external to the tail. This interpretation has been used to construct the rough approximation of the shape of the magnetospheric boundary on the evening side of the earth-sun line in the geomagnetic equatorial plane shown in Figure 2. The relative position of Gringauz' and Freeman's low energy fluxes with respect to the interpolated magnetospheric boundary of Figure 2 would imply that these electron fluxes are at least temporarily trapped within the geomagnetic field, but a critical judgment rests upon knowledge of the detailed character of the magnetic field in these regions. Hence the results of the large spatial survey of the geomagnetic field by Cahill's apparatus on Explorer XIV are anxiously awaited.

## VII. THE ROLE OF POLARIZATION ELECTRIC FIELDS IN CHARGED PARTICLE DYNAMICS OF THE MAGNETOSPHERE

The possibility that electric fields may play an important role in the dynamics of charged particle motion in the vicinity of the earth's magnetosphere has been stressed by various authors [cf. Chapman and Ferraro, 1931-33; Axford and Hines, 1961]. Indeed such an effect may account for the marked departure from rotational symmetry of the flux contours of electrons ($E \gtrsim 40$ keV) at local dawn as shown in Figure 6. The motion of charged particles in an inhomogeneous magnetic field and under the influence of external forces has been studied previously [Alfvén, 1950; Spitzer, 1962]. For motion in which the first adiabatic invariant $\mu = W_{\perp}/B$ is conserved, Figure 11 schematically depicts the corresponding drift motion for positive ions and electrons in an inhomogeneous magnetic field and an external electric field. These drifts or combinations of these drifts have provided several authors [cf. Kellogg, 1959; Parker, 1960; Herlofson, 1962] with a basic mechanism for populating the magnetosphere with charged particles by radial diffusion from a source; an example of such a source might be found in the vicinity of the magnetospheric boundary. Our specific realm of interest lies with the Chapman-Ferraro [1933] and Axford-Hines [1961] models of the magnetosphere. With regard to the Chapman-Ferraro model, Vestine [1963] has called attention to the fact that the polarization charge on the dawn and evening sides of the magnetospheric boundary induced by the flow of solar plasma through the magnetic field in the vicinity of the boundary results in an electric field (see Figure 12) across the cavity which is in a direction which will tend to drive positive ions and electrons along the boundary toward the earth. Axford and Hines [1961] have developed a model of the magnetosphere in which there is a convective interchange of geomagnetic tubes of force driven by corotation of the earth's magnetic field and/or a viscous interaction with the solar wind. The lines of constant potential of electric polarization for these two physical situations are displayed in Figure 13; the geophysical situation may actually be a linear combination of the two effects. An electron of say 50 keV would then experience a force associated with its gradient drift, which is $\mu \nabla B$, and that due to the polarization electric fields, $e\vec{E}$. In the Axford-Hines model of the magnetosphere if polarization fields predominate, the electrons and protons will stream essentially in the direction of the convection of the magnetic tubes of force (see Figure 13). Since the gradient drift is energy dependent and the electric drift is energy independent, the approximately azimuthal symmetry in the geomagnetic equatorial plane of the distributions of electrons of energy $E \gtrsim 230$ keV [Frank and Van Allen, unpublished] and the diverse distribution of electrons of energy

$E \lesssim 100$ keV may be important parameters in determining the magnitude of polarization electric fields if B and $\nabla$ B have been simultaneously measured and other drifts may be neglected. A similar study of the spatial distribution of protons would also be of significance since the direction of the gradient and electric drifts are charge-dependent and -independent, respectively. An interesting set of quantitative calculations of the drift paths and energy changes along these paths for energetic electrons and protons moving in a model magnetosphere under the influence of gradient drift in an image dipole field and polarization electric fields induced by a diurnal corotation of the geomagnetic field has been calculated by Hones [1963]. As an example, Hones finds that an energetic electron of 50 keV drifting in the geomagnetic equatorial plane at 7.2 $R_E$ at local noon will drift to 6.2 $R_E$ at local midnight. The spatial and energy distributions of charged particles within and near the magnetospheric boundary may become important instruments in understanding the dynamics of the earth's magnetosphere.

## VIII. SHOCKS, DEFORMATION, AND MOTION OF THE MAGNETOSPHERIC BOUNDARY

Various computations of the shape of the hollow carved out of the solar plasma flow by the earth's magnetic field have been performed [Beard, 1960, 1962; Spreiter and Briggs, 1962 a, b; Spreiter and Jones, 1963]. In Figure 14 are graphical displays of the results of three of these computations. Beard's [1960] result was based upon an interaction between the solar wind and the earth's magnetic field within a thin current sheath at the magnetospheric boundary; the shape of the boundary was determined by equating the pressure due to the solar wind on the sunward side of the hollow with the energy density of the diamagnetically enhanced geomagnetic field just inside the cavity. The results for a zero temperature and finite temperature plasma are shown in Figure 14. Spreiter and Briggs [1962 a, b] have performed a similar computation (see Figure 14) and more recently, Spreiter and Jones [1963] have recalculated the form of the cavity utilizing the experimental measurements of the solar wind with Mariner II [Neugebauer and Snyder, 1963]. The general shape of these cavities in the geomagnetic equatorial plane are consistent with the known experimental results (see Figures 2 and 6) but Heppner and his colleagues [1963] and Bonetti et al. [1963] have questioned some of the detailed structure of the interface on experimental grounds. Except for the single traversal of the magnetosphere at a geomagnetic latitude of $\sim 50°$ by Mars I, no direct experimental evidence concerning the form of the hollow in the meridianal planes at high latitudes is available at present.

Kellogg /1962/ (see also Axford /1962/ and Davis, Lüst, and Schlüter /1958/ ) has considered the supersonic flow of a collisionless solar plasma past the magnetosphere which acts as an obstacle to the flow and results in a shock wave on the sunward side of the geomagnetic hollow since any pressure wave of the frequency range expected, $\sim v_o / D$ (D is the dimension of the "bubble"), can be shown to propagate at velocities less than the bulk velocity $v_o$ of the solar plasma. The applicability to a collisionless plasma of the ordinary gas shock relationships which are used to construct the shocks of Figure 15 is not completely known but apparently can be partially justified if the plasma is permeated by a weak magnetic field /cf. Spreiter and Jones, 1963; Obayashi, 1962/. More recent computations by Spreiter and Jones /1963/ using an Alfvén Mach number $M_A$ in the range of the observed interplanetary experimental values are shown in Figure 14. Recently Freeman /1963/ has reported a persistent layer of low energy electrons (tens of ergs $(cm^2 \text{ sterad sec})^{-1}$) located just outside the sunward magnetospheric boundary near the geomagnetic plane with CdS total energy detectors on Explorer XII (see Figures 2 and 16).

This layer has a radial dimension of approximately 2 or 3 $R_E$ in agreement with the aforementioned theoretical results and may represent more direct experimental evidence of a shock on the sunward side of the magnetosphere. If the solar wind and the sunward side of the earth's magnetosphere are in a state of dynamic quasi-stationary equilibrium, it is reasonable to expect that a radial motion of the sunward boundary would be impressed by the action of the fluctuating solar wind. Along these lines of thought, Freeman [1963] has studied the position of the magnetospheric boundary, delineated by the radial termination of fluxes of electrons of energy ~ 40 keV, as a function of time with instrumentation on Explorer XII (see Figure 17). Along with a definite correlation with $D_{ST}$ as shown in Figure 17 the experimenter interprets these data as signifying a compression of the magnetosphere during the initial phase of a magnetic storm, a closer-than-average position maintained during the main phase and an outward motion of the boundary during the recovery phase. The fluctuation in the radial position of the boundary is approximately 2 or 3 $R_E$ about an average position of 10 $R_E$. It is of interest to also note that the standard surface parameter for solar plasma activity, $K_p$, has been shown experimentally to have a positive correlation with the velocity of the solar wind [Snyder and Neugebauer, 1963] and the variability of the energy fluxes observed by Explorer XII just outside the sunward side of the magnetospheric boundary [Freeman, 1963].

## IX. REMARK ON THE DAWN-EVENING DISTRIBUTION OF ENERGETIC ELECTRONS IN THE GEOMAGNETIC EQUATORIAL PLANE

It was noted earlier in our discussion that a preliminary survey /Frank, Van Allen, and Macagno, 1963/ of energetic electrons (40 keV $\leq$ E $\leq$ 230 keV) with Explorer XIV on the dawn side of the earth at large radial distances ( $\gtrsim$ 7 $R_E$) in the geomagnetic equatorial plane revealed a large asymmetry in the spatial distributions of electrons within the magnetosphere. These distributions are closely related to the shape of the magnetospheric boundary, the nature of the magnetic fields in the vicinity of these charged particles, and the dynamical processes occurring within the magnetosphere. A study of the spatial and temporal behavior of these particle fluxes on the evening side of the earth-sun line is thus of significant importance. Investigations of this nature are now possible by means of data recently acquired with Explorer XIV in these regions. This study has not advanced to the stage where it is possible to construct the contours of constant omnidirectional intensity of electrons on the evening side of the earth-sun line as has been done previously on the dawn side in Figure 6; but several interesting unpublished samples of Explorer XIV data are presented in Figures 20 through 22. Salient features of these slices through the earth's magnetosphere are briefly discussed here. (The graphs are presented in chronological order; apogee progresses from the dawn, through the night, and into the evening side of the magnetosphere.) Figure 18 shows the crossing of the magnetospheric boundary at 70,000 km at ~ 800 local time on 6-7 October 1962; Figure 19 displays measurements in the dawn flange where significant electron fluxes extend beyond the satellite's apogee radial range of 105,000 km; Figure 20 is exemplary of measurements in the night side of the magnetosphere where a dearth of energetic electrons exists beyond approximately 45,000 km; Figure 21 displays the counting rates of the same detector at local evening and demonstrates that significant fluxes of electrons extended beyond apogee in a similar fashion as at local dawn <u>for this particular pass</u>; Figure 22 presents a late pass when the satellite's apogee has progressed sufficiently toward the earth-sun direction to allow the instrumentation to pass through an apparent magnetospheric boundary on the evening side of the earth-sun line at 80,000 km. A detailed analysis of the composite Explorer XIV data will be of significant importance toward the understanding of magnetospheric boundary phenomena.

## X. SUMMARY

The highlights of our present experimental and theoretical knowledge of the magnetospheric boundary have been reviewed. A significant lack of experimental knowledge concerning the distribution of charged particles and the nature of the magnetic fields in the distant magnetosphere exists particularly concerning those regions at high geomagnetic latitudes and in the night side "tail" of the magnetosphere at geocentric radial distances exceeding 17 $R_E$ (cf. Figure 2). Progress has been made in many areas of study of the magnetospheric boundary. The general shape of the magnetosphere traced in the geomagnetic equatorial plane as predicted by the models of Beard /1960/ and Spreiter and his collaborators /1962 a, b; 1963/ are in substantial, although not complete, agreement with the observations of Explorers X, XII, and XIV. Also a true symmetry about the earth-sun line of the dawn and evening boundaries in the geomagnetic equatorial plane is yet to be shown. There now exists both theoretical and experimental support for the existence of a shock wave in front of the sunward side of the earth's magnetosphere as a result of a supersonic solar plasma flow past the earth's magnetosphere. Recent observations of the marked azimuthal asymmetries of the distributions of charged particles of a few tens of kilovolts of energy in the geomagnetic equatorial plane of the distant magnetosphere suggest that drift motions other than gradient drifts are effective in these regions and may be attributed to polarization electric fields. Such a study of the spatial distributions and temporal behavior of these charged particles may thus lead indirectly to a critical examination of various magnetospheric models such as those of Chapman and Ferraro [1931-1933] and Axford and Hines [1961]. The interlocking dependence of simultaneous charged particle and magnetic field measurements is easily seen to be vital throughout the interpretations reviewed in this survey. The subject of neutral points and possible charged particle injection mechanisms via the magnetospheric boundary have been neglected due to the lack of discriminating experimental information. It has been suggested that acceleration of charged particles exists in the vicinity of the distant magnetosphere and that the subsequent downflux of these particles along geomagnetic lines of force is responsible for various ionospheric phenomena such as aurorae. Utilization of recent experimental results concerning the average energy dumped into the atmosphere in the form of corpuscular energy and the average energy available to the magnetosphere from the solar wind enables us to estimate the gross efficiency of a magnetospheric acceleration mechanism in the following manner. The average energy downflux of electrons of energy $\gtrsim$ 1 keV into the auroral regions has been inferred from measurements with the low-altitude satellite

Injun I as approximately 1 erg $(cm^2\ sec)^{-1}$ [O'Brien, 1962]; via integration over the surface area of the earth where this dumping is significant ( ~ 55° to ~ 75° geomagnetic latitude), the average total power output to the earth's atmosphere becomes approximately $10^{18}$ ergs $(sec)^{-1}$. The average power input available to the magnetosphere can be obtained from the Mariner II measurements [Neugebauer and Snyder, 1962] of the average solar wind energy flux, ~ $3 \times 10^{-1}$ ergs $(cm^2\ sec)^{-1}$, and by assuming the gross dimensions of the magnetosphere are that of a disk 15 $R_E$ in diameter; the total power input becomes ~ $\pi\ (15\ R_E)^2\ (0.3)$ ~ $5 \times 10^{19}$ ergs $(sec)^{-1}$. The efficiency of this "black box" magnetosphere for producing the dumped corpuscular radiation from the energy available from the solar wind is hence of the order of $10^{18}/5 \times 10^{19} = 2\%$, a high, but apparently acceptable efficiency. Thus an acceleration mechanism for producing the corpuscular radiation observed to be dumped into the earth's atmosphere and located in the distant magnetosphere cannot be excluded on an energetic basis.

The close passage (41,000 km) of Mariner II past the planet Venus has been the only opportunity to observe the magnetosphere of another planet <u>in situ</u>; none of the Mariner II detectors (electrostatic analyzer, magnetometers, G.M. tubes) indicated the presence of a Venusian magnetosphere [Smith, Davis, Coleman, and Sonett, 1963; Frank, Van Allen, and Hills, 1963].

Definite progress has been accomplished since the advent of space probes and earth satellites toward the understanding of the processes occurring in the vicinity of the magnetospheric boundary, a region which is intimately associated with the sun via the solar wind and which in turn may have a profound influence upon the physics of the upper atmosphere; the next few years of experimental and theoretical study of these phenomena show great promise in being fruitful ones.

## BIBLIOGRAPHY

Alfvén, H., Cosmical Electrodynamics, Oxford at the Clarendon Press (1950).

Akasofu, S.-I., and S. Chapman, "A Neutral Line Discharge Theory of the Aurora Polaris", Phil. Trans. Roy. Soc. London A253, 359-406 (1961).

Arnoldy, R. L., R. A. Hoffman, and J. R. Winckler, "Observations of the Van Allen Radiation Regions During August and September, 1959, Part I", J. Geophys. Research 65, 1361-1376 (1960).

Axford, W. I., "The Interaction between the Solar Wind and the Earth's Magnetosphere", J. Geophys. Research 67, 3791-3796 (1962).

Axford, W. I., and C. O. Hines, "A Unifying Theory of High-Latitude Geophysical Phenomena and Geomagnetic Storms", Can. J. Phys. 39, 1322 (1961).

Beard, D. B., "The Interaction of the Terrestrial Magnetic Field with the Solar Corpuscular Radiation", J. Geophys. Research 65, 3559-3568 (1960).

Beard, D. B., "The Interaction of the Terrestrial Magnetic Field with the Solar Corpuscular Radiation. 2. Second Order Approximation", J. Geophys. Research 67, 477-483 (1962).

Bonetti, A., H. S. Bridge, A. J. Lazarus, B. Rossi, and F. Scherb, "Explorer 10 Plasma Measurements", J. Geophys. Research 68, 4017-4064 (1963).

Bridge, H. S., C. Dilworth, A. Lazarus, E. F. Lyon, Rossi, and F. Scherb, "Direct Observations of the Interplanetary Plasma", J. Phys. Soc. Japan 17, Suppl. II A, 553 (1962).

Cahill, L. J., Paper Presented at the Explorer XIV Symposium, Washington, D. C., February 1963.

Cahill, L. J., and P. G. Amazeen, "The Boundary of the Geomagnetic Field", J. Geophys. Research 68, 1835 (1963).

Chapman, S., and V. C. A. Ferraro, "A New Theory of Magnetic Storms", Terrestrial Magnetism and Electricity, June 1931; September 1931; June 1932; December 1932; June 1933.

Coleman, P. J., L. Davis, Jr., E. J. Smith, and C. P. Sonett, "Interplanetary Magnetic Fields" (in Mariner II), Science 138, 1099-1100 (1962).

Coleman, P. J., and C. P. Sonett, "Note on Hydromagnetic Propagation and Geomagnetic Field Stability", J. Geophys. Research 66, 3591-3592 (1961).

Coleman, Jr., P. J., C. P. Sonett, D. L. Judge, and E. J. Smith, "Some Preliminary Results of the Pioneer V Magnetometer Experiment", J. Geophys. Research 65, 1856-1857 (1960).

Davis, L. R., Paper Presented at the Explorer XIV Symposium, Washington, D. C., February 1963.

Davis, L. R., and J. M. Williamson, "Low-Energy Trapped Protons", Paper Presented at Third International Space Science Symposium (COSPAR), Washington, D. C., May 1962.

Davis, Jr., L., R. Lüst, and A. Schlüter, "The Structure of Hydromagnetic Shock Waves", Z. Naturforsch., 13a, 916 (1958).

Dessler, A. J., "Large Amplitude Hydromagnetic Waves above the Ionosphere", J. Geophys. Research 63, 507-511 (1958).

Dessler, A. J., "The Stability of the Interface between the Solar Wind and the Geomagnetic Field", J. Geophys. Research 66, 3587-3590 (1961).

Dessler, A. J., and E. N. Parker, "Hydromagnetic Theory of Geomagnetic Storms", J. Geophys. Research 64, 2239-2252 (1959).

Frank, L. A., J. A. Van Allen, and H. K. Hills, "Charged Particles" (near Venus with Mariner II), Science 139, 905-907 (1963).

Frank, L. A., J. A. Van Allen, and E. Macagno, "Charged Particle Observations in the Earth's Outer Magnetosphere", J. Geophys. Research 68, 3543-3554 (1963).

Frank, L. A., J. A. Van Allen, W. A. Whelpley, and J. D. Craven, "Absolute Intensities of Geomagnetically Trapped Particles with Explorer XIV", J. Geophys. Research 68, 1573-1579 (1963).

Freeman, J. W., "The Morphology of the Electron Distribution in the Outer Radiation Zone and Near the Magnetospheric Boundary as Observed by Explorer XII", State University of Iowa Report 63-20 (1963).

Freeman, J. W., J. A. Van Allen, and L. J. Cahill, Jr., "Explorer XII Observations of the Magnetospheric Boundary and the Associated Solar Plasma on the 13th of September 1961", J. Geophys. Research 68, 2121-2130 (1963).

Gringauz, K. I., V. V. Bezrukikh, L. S. Musatov, R. E. Rybchinsky, and S. M. Sheronova, "Measurements Made in the Earth's Magnetosphere by Means of Charged Particle Traps Aboard the Mars I Probe", Paper Presented at the Fourth International Space Science Symposium (COSPAR), Warsaw, Poland, June 1963.

Gringauz, K. I., V. G. Kurt, V. I. Moroz, and I. S. Shklovskii, "Results of Observations of Charged Particles Observed Out to R = 100,000 km, with the Aid of Charged-Particle Traps on Soviet Space Rockets", Soviet Astronomy (AJ) 4, 680-695 (1961).

Heppner, J. P., N. F. Ness, C. S. Scearce, and T. L. Skillman, "Explorer X Magnetic Field Measurements", J. Geophys. Research 68, 1-46 (1963).

Hoffman, R. A., R. L. Arnoldy, and J. R. Winckler, "Observations of the Van Allen Radiation Regions During August and September 1959, Part 6: Properties of the Outer Region", J. Geophys. Research 67, 4543-4573 (1962).

Hones, E. W., "Motions of Charged Particles Trapped in the Earth's Magnetosphere", J. Geophys. Research 68, 1209-1220 (1963).

Johnson, F. S., "The Gross Character of the Geomagnetic Field in the Solar Wind", J. Geophys. Research 65, 3049-3052 (1960).

Kellogg, P. J., "Van Allen Radiation of Solar Origin", Nature 183, 1295 (1959).

Kellogg, P. J., "Flow of Plasma Around the Earth", J. Geophys. Research 67, 3805-3811 (1962).

MacDonald, G. J. F., "Spectrum of Hydromagnetic Waves in the Exosphere", J. Geophys. Research 66, 3639-3670 (1961).

McIlwain, C. E., "Coordinates for Mapping the Distribution of Magnetically Trapped Particles", J. Geophys. Research 66, 3681-3692 (1961).

Neugebauer, M., and C. W. Snyder, "The Solar Plasma Experiment" (in Mariner II), Science 138, 1095-1097 (1962).

Obayashi, T., "Interaction of Solar Plasma Streams with the Outer Geomagnetic Field", Paper Presented at the Symposium on Cosmic Plasma Physics, Institute of Plasma Physics, Nagoya University, November 1962.

O'Brien, B. J., "Lifetimes of Outer-Zone Electrons and Their Precipitation into the Atmosphere", J. Geophys. Research 67, 3687-3706 (1962).

O'Brien, B. J., "A Large Diurnal Variation of the Geomagnetically Trapped Radiation", J. Geophys. Research 68, 989-996 (1963).

Parker, E. N., "Interaction of the Solar Wind with the Geomagnetic Field", Phys. Fluids 1, 171 (1958).

Parker, E. N., "Geomagnetic Fluctuations and the Form of the Outer Zone of the Van Allen Radiation Belt", J. Geophys. Research 65, 3117-3130 (1960).

Smith, E. J., "Theoretical and Experimental Aspects of Ring Currents", Space Science, Chapter 9, pp. 316-371. Wiley and Sons, Inc., New York, 1963.

Smith, E. J., L. Davis, Jr., P. J. Coleman, and C. P. Sonett, "Magnetic Field" (near Venus with Mariner II), Science 139, 909-910 (1963).

Snyder, C. W., and M. Neugebauer, "Interplanetary Solar Wind Measurements by Mariner II", Paper Presented at the Fourth International Space Science Symposium (COSPAR), Warsaw, Poland, June 1963.

Sonett, C. P., "Rocket Experiments in Cosmic Magnetism and Their Significance", Space Science, Chapter 10, 374-421. Wiley and Sons, Inc., New York, 1963.

Sonett, C. P., "The Distant Geomagnetic Field. Part 4. Microstructure of a Disordered Hydromagnetic Medium in the Collisionless Limit", J. Geophys. Research 68, 1265-1294 (1963).

Sonett, C. P., E. J. Smith, and A. R. Sims, "Surveys of the Distant Magnetic Field: Pioneer I and Explorer VI", Proc. First International Space Sci. Symposium (1960).

Spitzer, L., Physics of Fully Ionized Gases, Interscience Publishers (John Wiley and Sons), New York (1962).

Spreiter, J. R., and B. R. Briggs, "Theoretical Determination of the Form of the Hollow Produced in the Solar Corpuscular Stream by Interaction with the Magnetic Dipole of the Earth", J. Geophys. Research 67, 2983-2985 (1962a).

Spreiter, J. R., and B. R. Briggs, "On the Choice of Condition to Apply at the Boundary of the Geomagnetic Field in the Steady-State Chapman-Ferraro Problem", J. Geophys. Research 67, 2983-2985 (1962b).

Spreiter, J. R., and W. P. Jones, "On the Effect of a Weak Interplanetary Magnetic Field on the Interaction between the Solar Wind and the Geomagnetic Field", J. Geophys. Research 68, 3555-3564 (1963).

Vakulov, P. V., S. N. Vernov, E. B. Gorchakov, Yu. I. Logachev, A. N. Charakhchyan, T. N. Charakhychyan, and A. E. Chudakov, "Investigation of Cosmic Rays", Paper Presented at the Fourth International Space Science Symposium, Warsaw, Poland, June 1963.

Van Allen, J. A., and L. A. Frank, "Radiation Around the Earth to a Radial Distance of 107,400 Kilometers", Nature (London) 183, 430-434 (1959a).

Van Allen, J. A., and L. A. Frank, "Radiation Measurements to 658,000 km with Pioneer IV", Nature (London) 184, 219-224 (1959b).

Van Allen, J. A., and L. A. Frank, "The Iowa Radiation Experiment", (in Mariner II), Science 138, 1098-1099 (1962).

Vernov, S. N., A. E. Chudakov, P. V. Valukov, Yu. I. Logachev, and A. G. Nikolaev, "Radiation Measurements During the Flight of the Second Lunar Rocket", Artificial Earth Satellites, Vols. 3, 4, and 5, pp. 503-511. Plenum Press, Inc., New York, 1961.

Vestine, E. H., "Some Comments on the Ionosphere and Geomagnetism", Paper to be Presented at the XIVth General Assembly of the International Scientific Radio Union, Tokyo, Japan, September 1963.

## FIGURE CAPTIONS

Figure 1. Graphical summary of the trajectories of several probes and satellites with respect to the earth-sun line and projected onto the geomagnetic equatorial plane: Pioneer III, 6-7 December 1958; Pioneer IV, 3 March 1959; Lunik II, 12 September 1959; Explorer X, 25-28 March 1961; Explorer VI, August-October 1959; Explorer XII, August-December 1961; Explorer XIV, October 1962 to present (July 1963).

Figure 2. Graphical summary of principal measurements of low energy charged particles in the geomagnetic equatorial plane beyond $\sim 7\ R_E$.

Figure 3. Comparison of the responses of the similar, heavily shielded G.M. tubes on Pioneer III and Explorer XII for similar trajectories with respect to the earth-sun line (see legend at upper left).

Figure 4. Comparison of the responses of similar, heavily shielded G.M. tubes on Pioneer IV and Explorer XIV for similar trajectories with respect to the earth-sun line. The consistently higher response of the Pioneer IV detector may be due to an enhancement of energetic electrons ($E \sim 50$ keV) following pronounced geomagnetic and solar activity.

Figure 5. Comparison of the responses of similar, heavily shielded G.M. tubes on Explorers VI and XIV for similar trajectories with respect to the earth-sun line. Compare the distance of onset of negligible response of $\sim 45{,}000$ km with those of Figures 3 and 4.

Figure 6. Graphical summary of measurements of energetic electrons ($E \gtrsim 40$ keV) in the geomagnetic equatorial plane with Explorers XII and XIV on the dawn side of the earth-sun line (see text).

Figure 7. Latitude profiles of the intensity of trapped electrons obtained in ten passes with local time between 1200 and 1600 hours (local day) and in eleven passes with local time between 1900 and 2300 hours (local night) soon after launch when the satellite was spinning rapidly [after O'Brien, 1963]. Note the variation of these two graphs with respect to the limit of observed trapped-particle intensity as a function of increasing L indicated by the lines enveloping all data points in each graph.

Figure 8. Illustrative drawing summarizing experimental measurements of charged particles and plausible distortions of the geomagnetic field in the meridianal plane containing the earth-sun line. (Mars I energetic electron measurements have also been included. See text.)

Figure 9. Particle and magnetic field measurements with Explorer XII for the inbound pass on September 13, 1961. The CdSB (magnet in aperture) detector count-rate has been normalized to the energy scale of the CdSTE (no magnet in aperture) detector. The counting rates of both CdS detectors are nearly linear with energy flux. Both spectrometer channels (SpL and SpH) have been corrected for background counts by the subtraction of the counting rate of the background detector SpB. The CdS optical monitor (not shown) indicated that during this pass the CdS detectors did not have any bright objects within their field of view. F denotes the scalar magnetic field strength; $\alpha$ the angle between the F-vector and the spin-axis of the satellite; and $\psi$ the dihedral angle between the plane containing the F-vector and the spin axis and the plane containing the spin axis and the satellite-sun line [after Freeman, Van Allen, and Cahill, 1963]. The experimenters found the measurements consistent

with an electron flux of $3 \times 10^{10}$ $(cm^2\ sec)^{-1}$ and with an energy of 2.6 keV per electron.

Figure 10. Pictorial summary of combined results of Pioneer I, Pioneer V, and Explorer XII showing the boundary of the geomagnetic cavity and the location of the bow wave (after Bonetti, Bridge, Lazarus, Rossi, and Scherb [1963] ). Local times for these probes are given in the text.

Figure 11. Illustrative diagram of gradient drift and electric field drift motions of positive ions and electrons.

Figure 12. [After Chapman and Ferraro, 1933] The hollow and the polarization charge distribution formed by the interaction of the geomagnetic field with the solar wind.

Figure 13. An equatorial section of the magnetosphere viewed from above the North Pole, showing streamlines for the case in which the magnetosphere is corotating with the earth. The streamlines are also equipotentials of electric polarization that is induced by the rotation (top figure) [after Axford and Hines, 1961].

The proposed pattern of streamlines in the equatorial plane (or alternately of the equipotentials of the electric field) resulting from the motion impressed on the magnetosphere by a viscous-like interaction with the solar wind (bottom figure) [after Axford and Hines, 1961].

Figure 14. Several results of computations concerning the form of the hollow produced by the interaction of the solar wind with the geomagnetic field.

Figure 15. Structure of the flow of interplanetary plasma around the earth for various supersonic flow speeds [after Kellogg, 1962]. The experimental Alfvén Mach number is ~ 7 (see text).

Figure 16. Explorer XII observations (22 September 1962) of a region of large electron flux (50 ergs $(cm^2 \text{ sterad sec})^{-1}$ at maximum) observed over a geocentric radial range of 55,000 to 67,500 km lying just beyond the magnetospheric boundary identified by the termination of ~ 50 keV electron fluxes (SpL) [after Freeman, 1963].

Figure 17. The time history of the radial position of the magnetospheric boundary as determined by the radial termination of counts above background in the SpL detector (Explorer XII). Also shown is the $D_{ST}$ (H) value from the San Juan and Honolulu magnetograms [after Freeman, 1963].

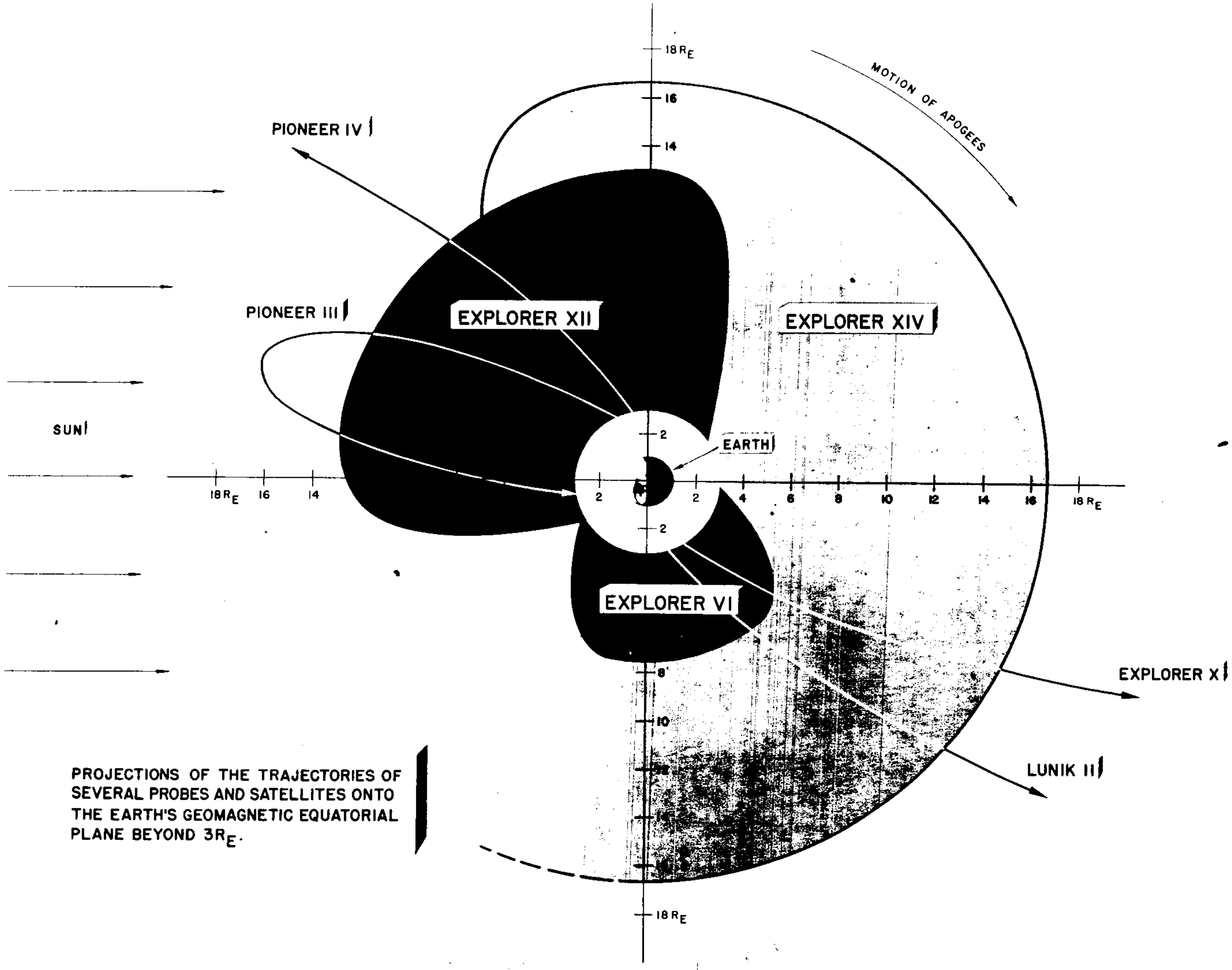
Figure 18. The first of a series of radial plots of the response of the 213 A detector (E - electrons $\gtrsim$ 40 keV) on Explorer XIV. The graphs are given in chronological order (and hence from local dawn to local evening). Conversion factor: $J_o$ (E $\gtrsim$ 40 keV) $\simeq 5 \times 10^3$ R $(cm^2 \text{ sec})^{-1}$. In this figure Explorer XIV crossed the magnetospheric boundary at 72,000 km on the dawn side of the earth-sun line. At 60,000 km, the local time was ~ 0830 [after Frank, Van Allen, and Macagno, 1963].

Figure 19. Measurements with the Explorer XIV 213 A electron detector near the dawn flange. At 60,000 km, the local time was ~ 0400 [after Frank, Van Allen, and Macagno, 1963].

Figure 20. Measurements on the night side of earth where there is a dearth of electrons. Note the sudden decrease of electron intensities at ~ 40,000 km. Local time at 60,000 km was ~ 2200 [Frank and Van Allen, unpublished].

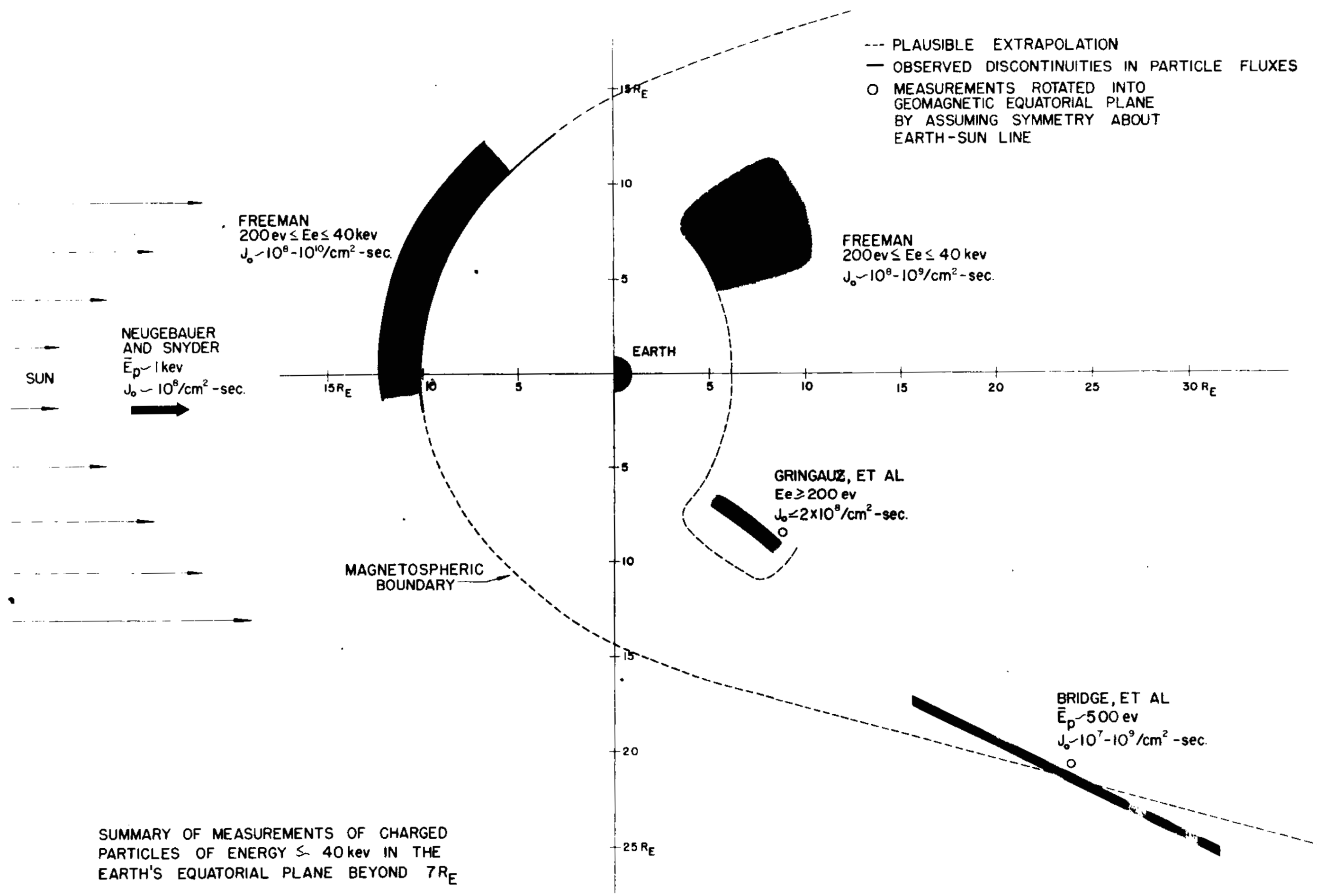
Figure 21. An interesting pass through the magnetosphere near local evening. Note that large, sporadic electron intensities persist at least to 100,000 km. Local time at 60,000 km was ~ 1900 [Frank and Van Allen, unpublished].

Figure 22. Another 213 A contour, but now with Explorer XIV nearer to the earth-sun line, in which an apparent traversal of the evening magnetospheric boundary has occurred. Local time at 60,000 km was ~ 1700 [Frank and Van Allen, unpublished].



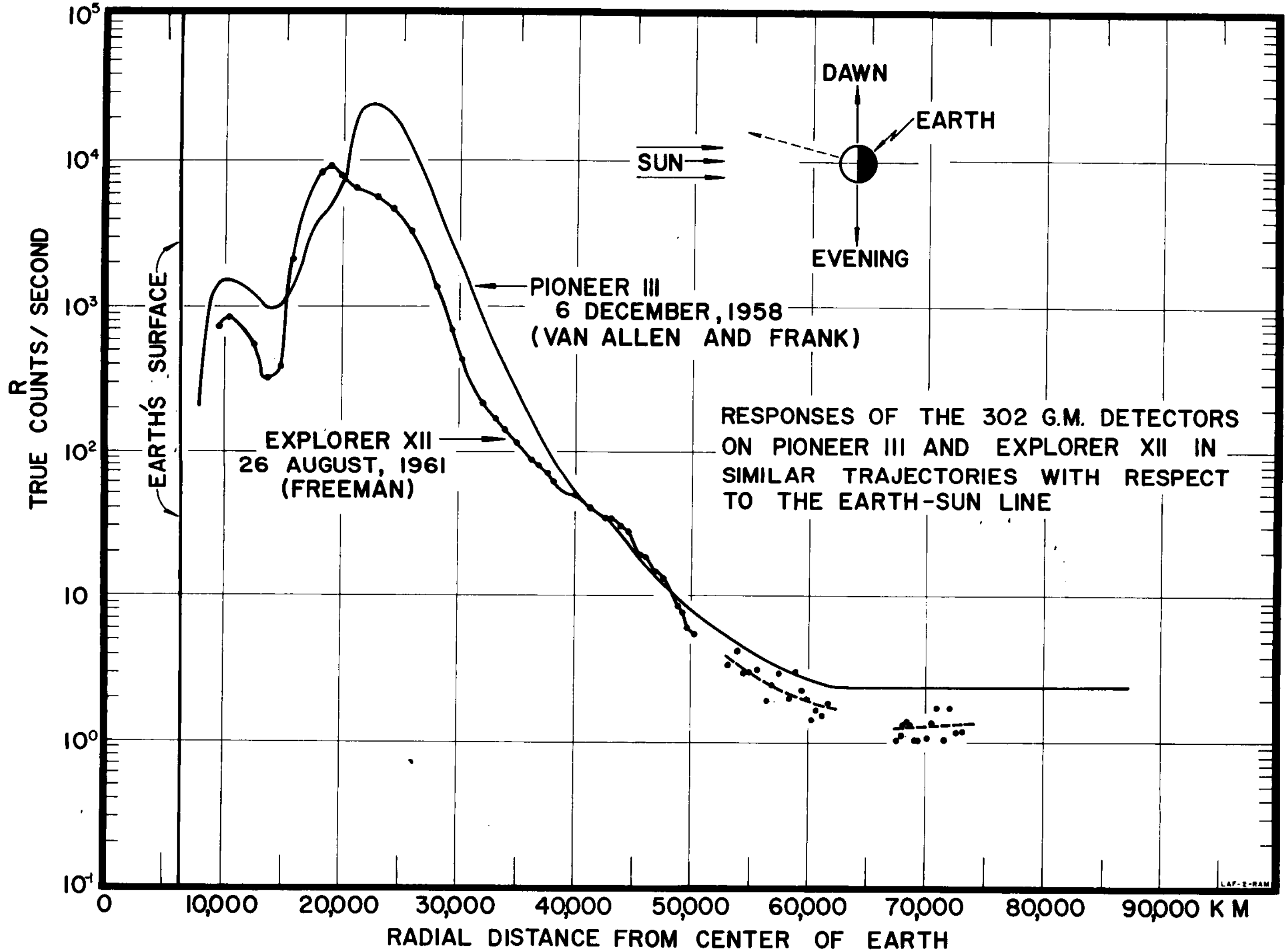

PROJECTIONS OF THE TRAJECTORIES OF SEVERAL PROBES AND SATELLITES ONTO THE EARTH'S GEOMAGNETIC EQUATORIAL PLANE BEYOND $3R_E$.

Figure 1



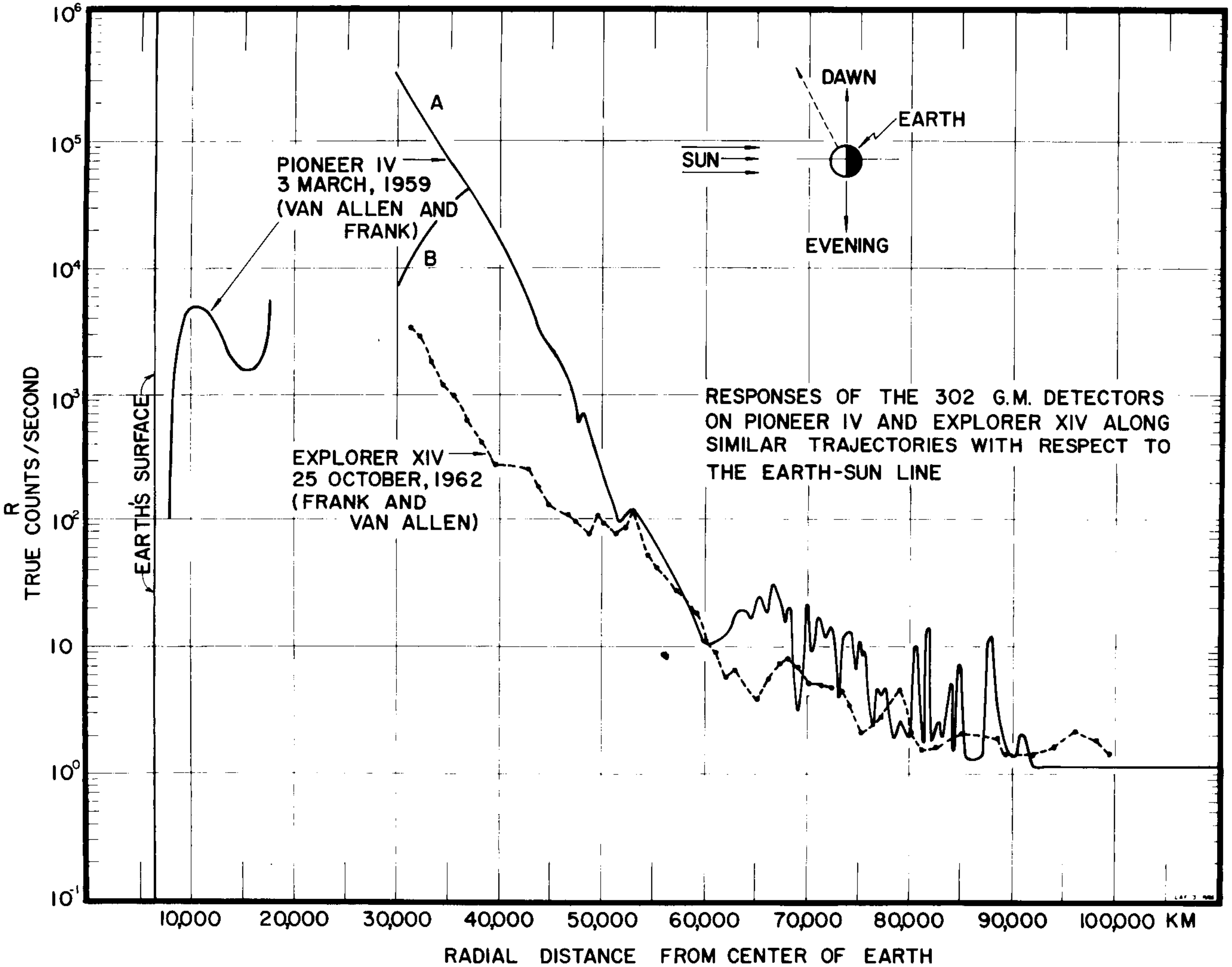

SUMMARY OF MEASUREMENTS OF CHARGED PARTICLES OF ENERGY ≲ 40 kev IN THE EARTH'S EQUATORIAL PLANE BEYOND 7 $R_E$

**Figure 2**



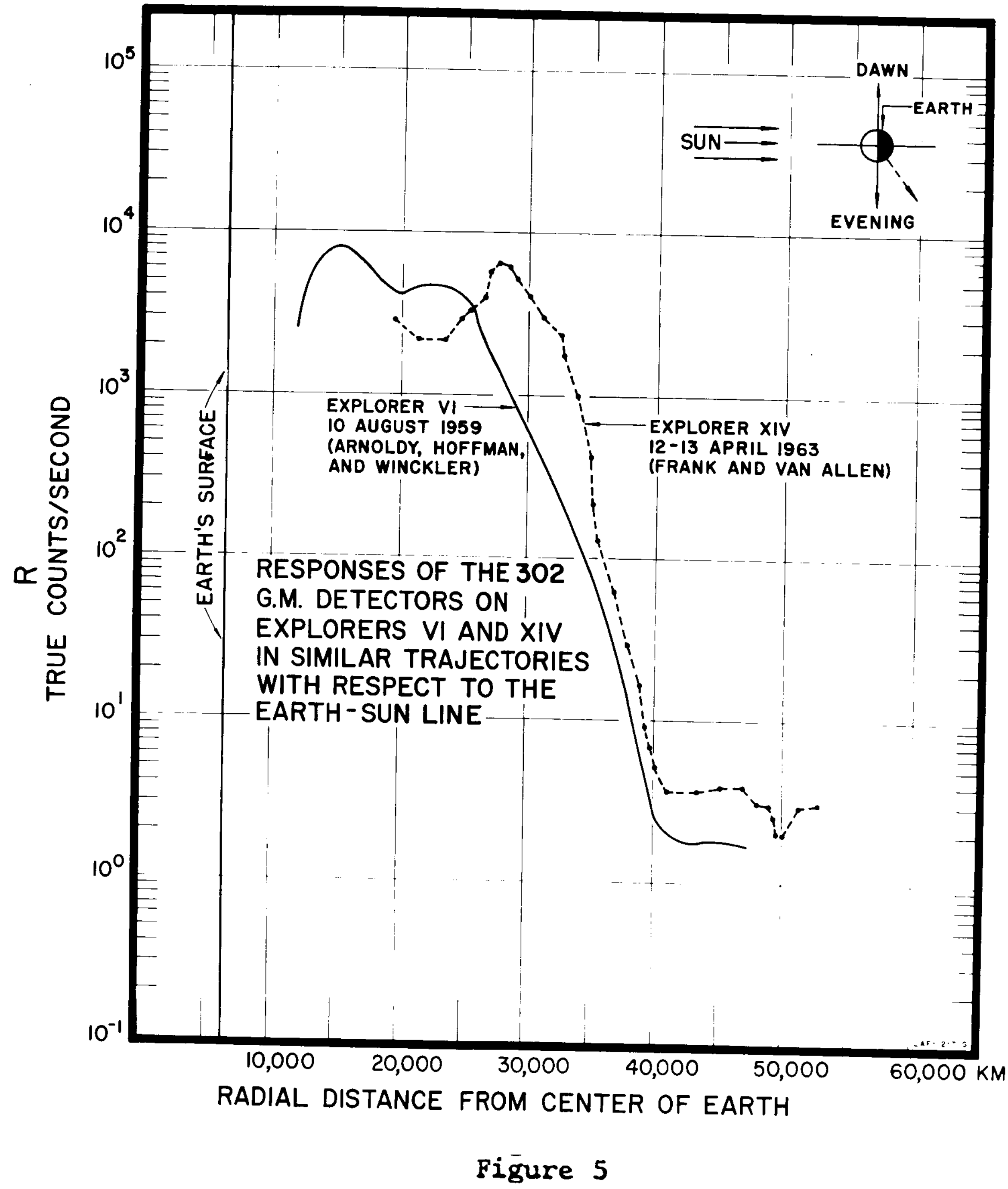
$10^5$
$10^4$
$10^3$
$10^2$
10
$10^0$
$10^{-1}$
R
TRUE COUNTS/ SECOND
EARTH'S SURFACE
SUN
DAWN
EARTH
EVENING
PIONEER III
6 DECEMBER, 1958
(VAN ALLEN AND FRANK)
EXPLORER XII
26 AUGUST, 1961
(FREEMAN)
RESPONSES OF THE 302 G.M. DETECTORS
ON PIONEER III AND EXPLORER XII IN
SIMILAR TRAJECTORIES WITH RESPECT
TO THE EARTH-SUN LINE
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000 K M
RADIAL DISTANCE FROM CENTER OF EARTH


Figure 3



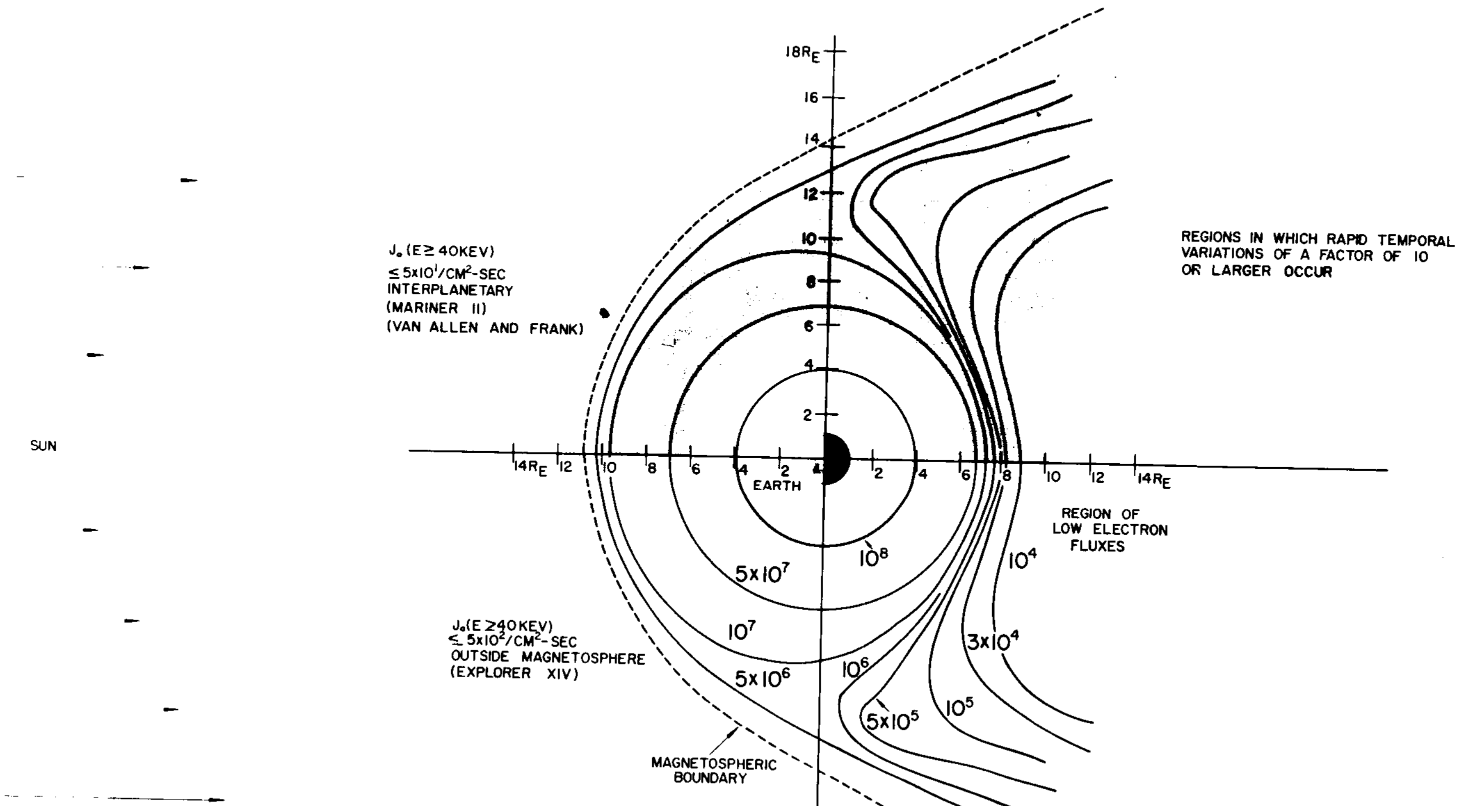
$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
10
$10^0$
$10^{-1}$
$R$
TRUE COUNTS/SECOND
EARTH'S SURFACE
A
B
PIONEER IV
3 MARCH, 1959
(VAN ALLEN AND
FRANK)
EXPLORER XIV
25 OCTOBER, 1962
(FRANK AND
VAN ALLEN)
SUN
DAWN
EARTH
EVENING
RESPONSES OF THE 302 G.M. DETECTORS
ON PIONEER IV AND EXPLORER XIV ALONG
SIMILAR TRAJECTORIES WITH RESPECT TO
THE EARTH-SUN LINE
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
100,000 KM
RADIAL DISTANCE FROM CENTER OF EARTH


**Figure 4**



DAWN
EARTH
SUN
EVENING
$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
R
TRUE COUNTS/SECOND
EARTH'S SURFACE
EXPLORER VI
10 AUGUST 1959
(ARNOLDY, HOFFMAN, AND WINCKLER)
EXPLORER XIV
12-13 APRIL 1963
(FRANK AND VAN ALLEN)
RESPONSES OF THE 302 G.M. DETECTORS ON EXPLORERS VI AND XIV IN SIMILAR TRAJECTORIES WITH RESPECT TO THE EARTH-SUN LINE
10,000
20,000
30,000
40,000
50,000
60,000 KM
RADIAL DISTANCE FROM CENTER OF EARTH


Figure 5




QUASI - STATIONARY CONTOURS OF CONSTANT OMNIDIRECTIONAL FLUX OF ELECTRONS (E ≥ 40KEV) IN THE MAGNETIC EQUATORIAL PLANE AS MEASURED WITH EXPLORERS XII & XIV SUMMARY OF MEASUREMENTS ON DAWN SIDE. (FRANK, VAN ALLEN AND MACAGNO)

**Figure 6**

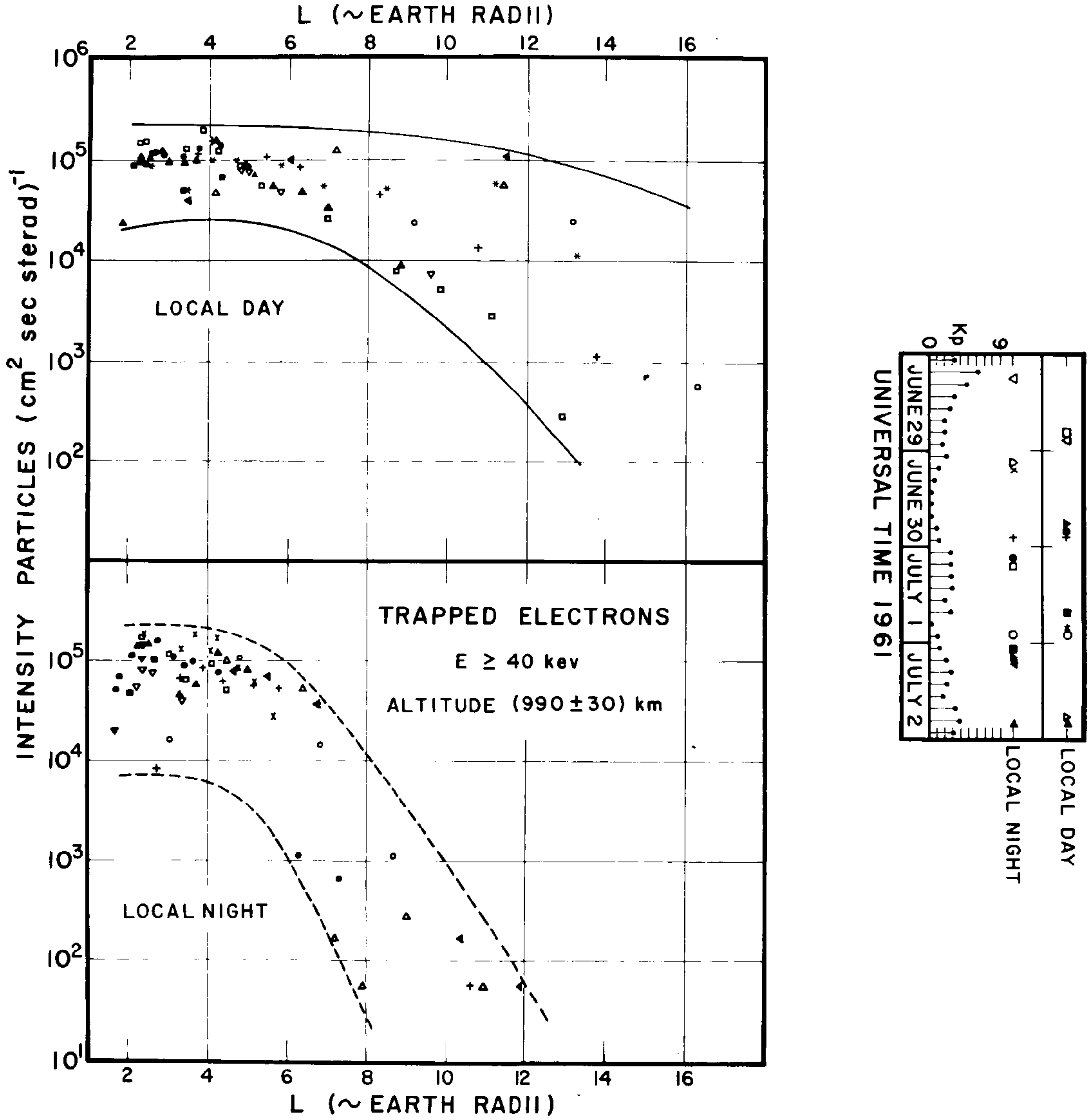
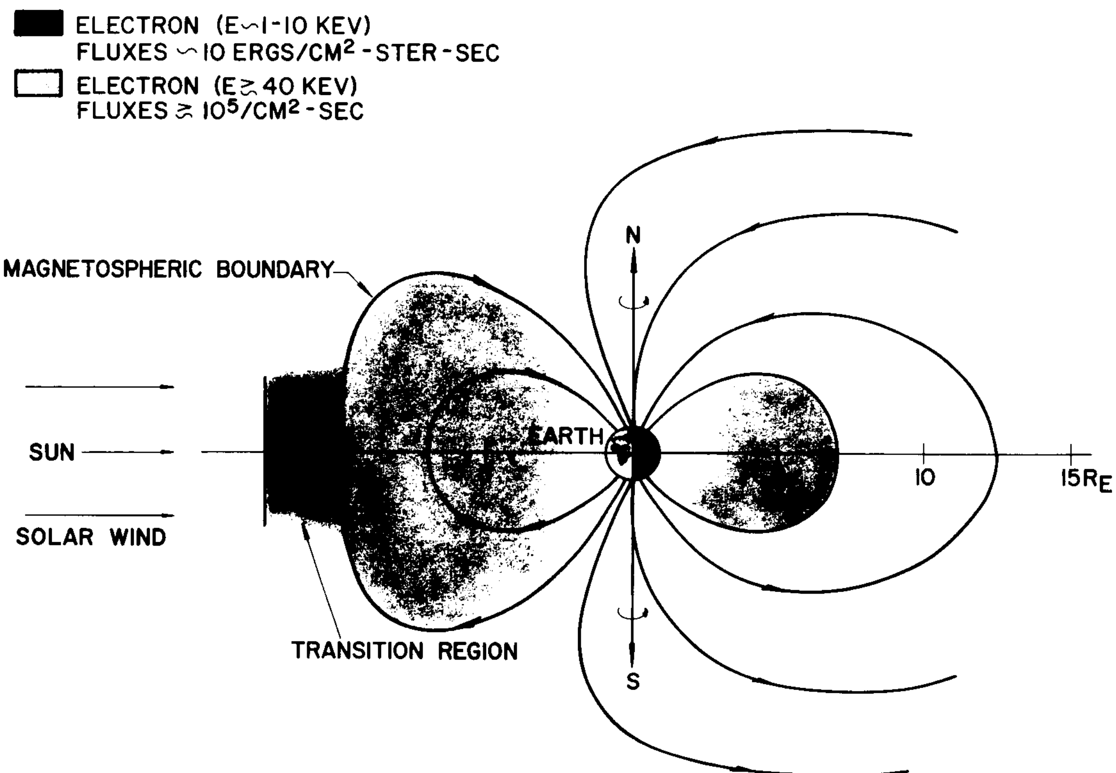
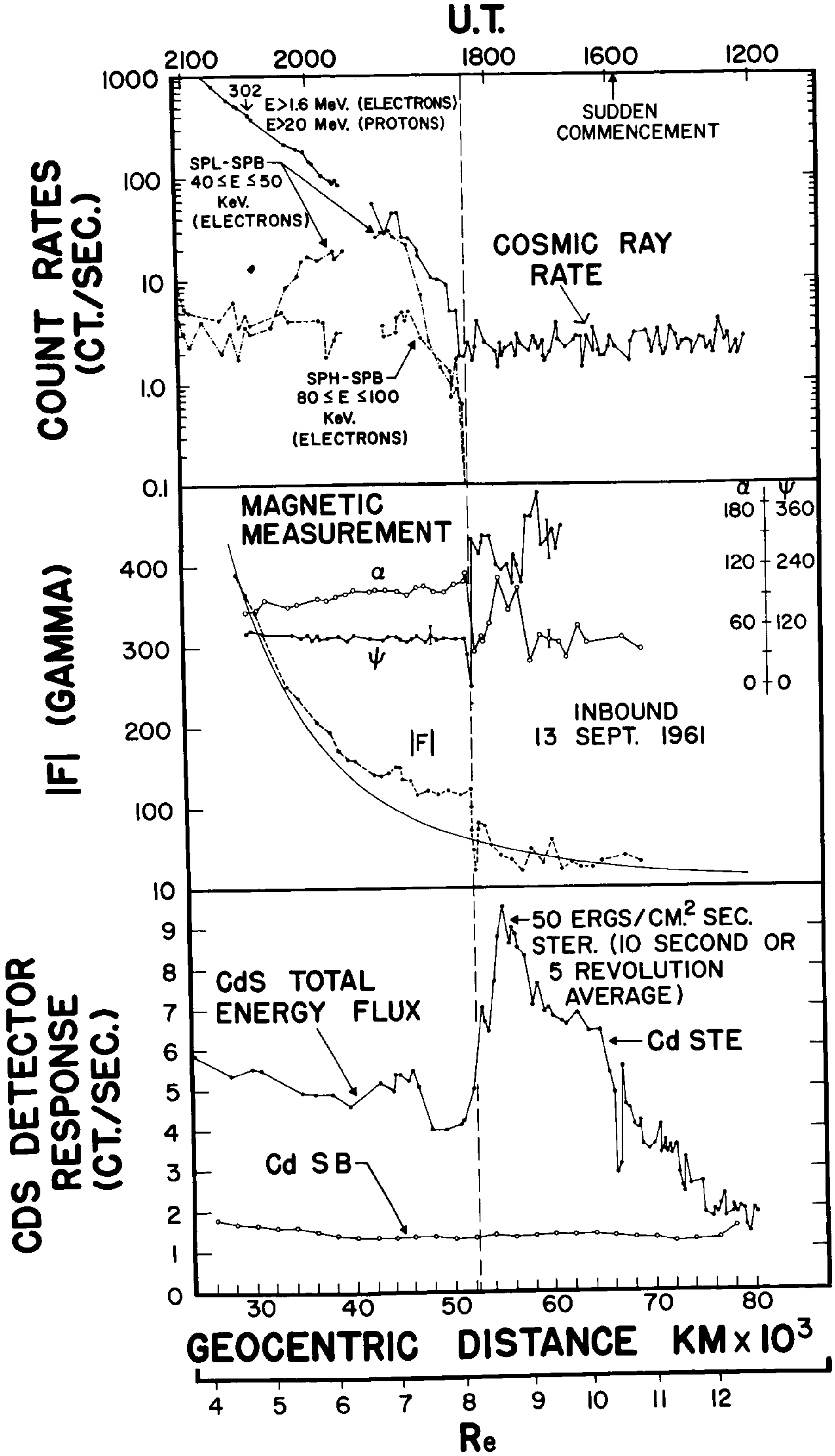

L (~EARTH RADII)
INTENSITY PARTICLES (cm² sec sterad)⁻¹
LOCAL DAY
TRAPPED ELECTRONS
E ≥ 40 kev
ALTITUDE (990±30) km
LOCAL NIGHT
LEGEND
LOCAL DAY
LOCAL NIGHT
Kp
UNIVERSAL TIME 1961
JUNE 29
JUNE 30
JULY 1
JULY 2

Figure 7




SUMMARY OF THE GROSS STRUCTURE OF THE DISTANT MAGNETOSPHERE IN THE MERIDIANAL PLANE CONTAINING THE EARTH-SUN LINE

**Figure 8**



U.T.
2100
2000
1800
1600
1200
1000
302
E>1.6 MeV. (ELECTRONS)
E>20 MeV. (PROTONS)
SUDDEN
COMMENCEMENT
SPL-SPB
40≤E≤50
KeV.
(ELECTRONS)
COSMIC RAY
RATE
SPH-SPB
80≤E≤100
KeV.
(ELECTRONS)
COUNT RATES
(CT./SEC.)
MAGNETIC
MEASUREMENT
α
ψ
|F|
INBOUND
13 SEPT. 1961
|F| (GAMMA)
CdS TOTAL
ENERGY FLUX
50 ERGS/CM.² SEC.
STER. (10 SECOND OR
5 REVOLUTION
AVERAGE)
Cd STE
Cd SB
CDS DETECTOR
RESPONSE
(CT./SEC.)
GEOCENTRIC DISTANCE KM x 10³
Re


Figure 9

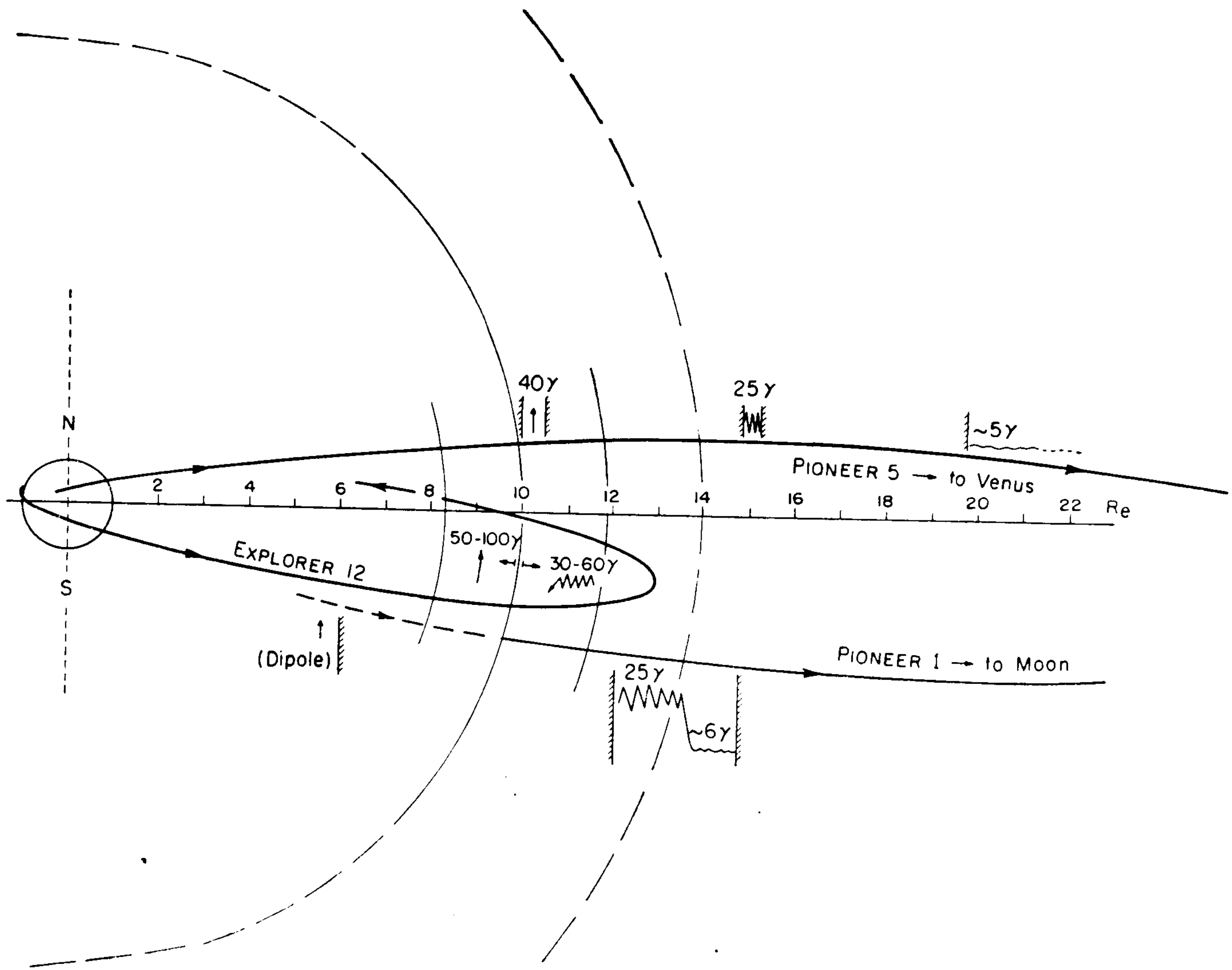
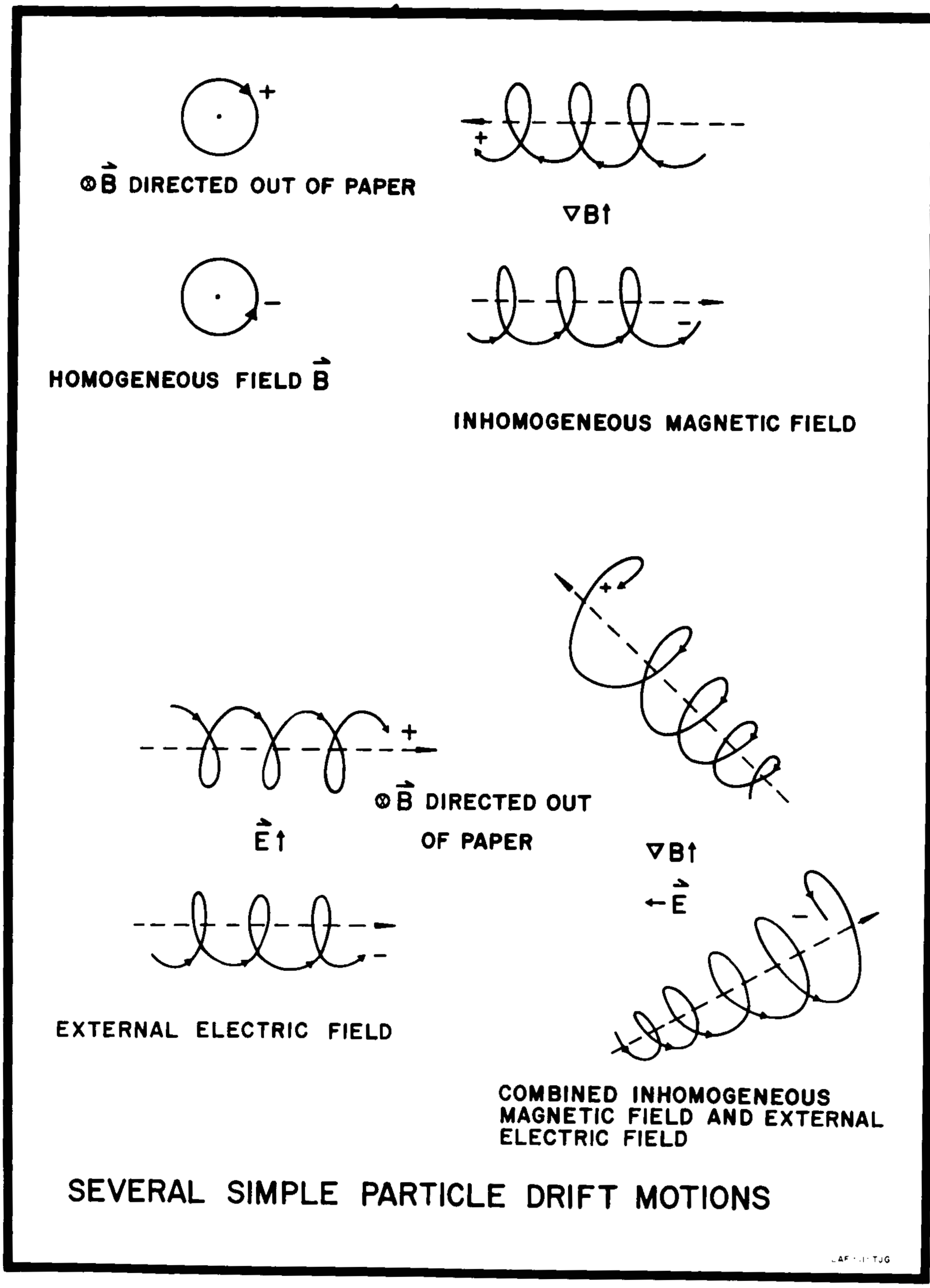

N
S
2
4
6
8
10
12
14
16
18
20
22
Re
40γ
25γ
~5γ
PIONEER 5 → to Venus
EXPLORER 12
50-100γ
30-60γ
(Dipole)
25γ
~6γ
PIONEER 1 → to Moon

Figure 10



+
⊗B DIRECTED OUT OF PAPER
−
HOMOGENEOUS FIELD B
+
∇B↑
−
INHOMOGENEOUS MAGNETIC FIELD
+
⊗B DIRECTED OUT
OF PAPER
E↑
−
EXTERNAL ELECTRIC FIELD
+
∇B↑
←E
−
COMBINED INHOMOGENEOUS
MAGNETIC FIELD AND EXTERNAL
ELECTRIC FIELD
SEVERAL SIMPLE PARTICLE DRIFT MOTIONS


Figure 11

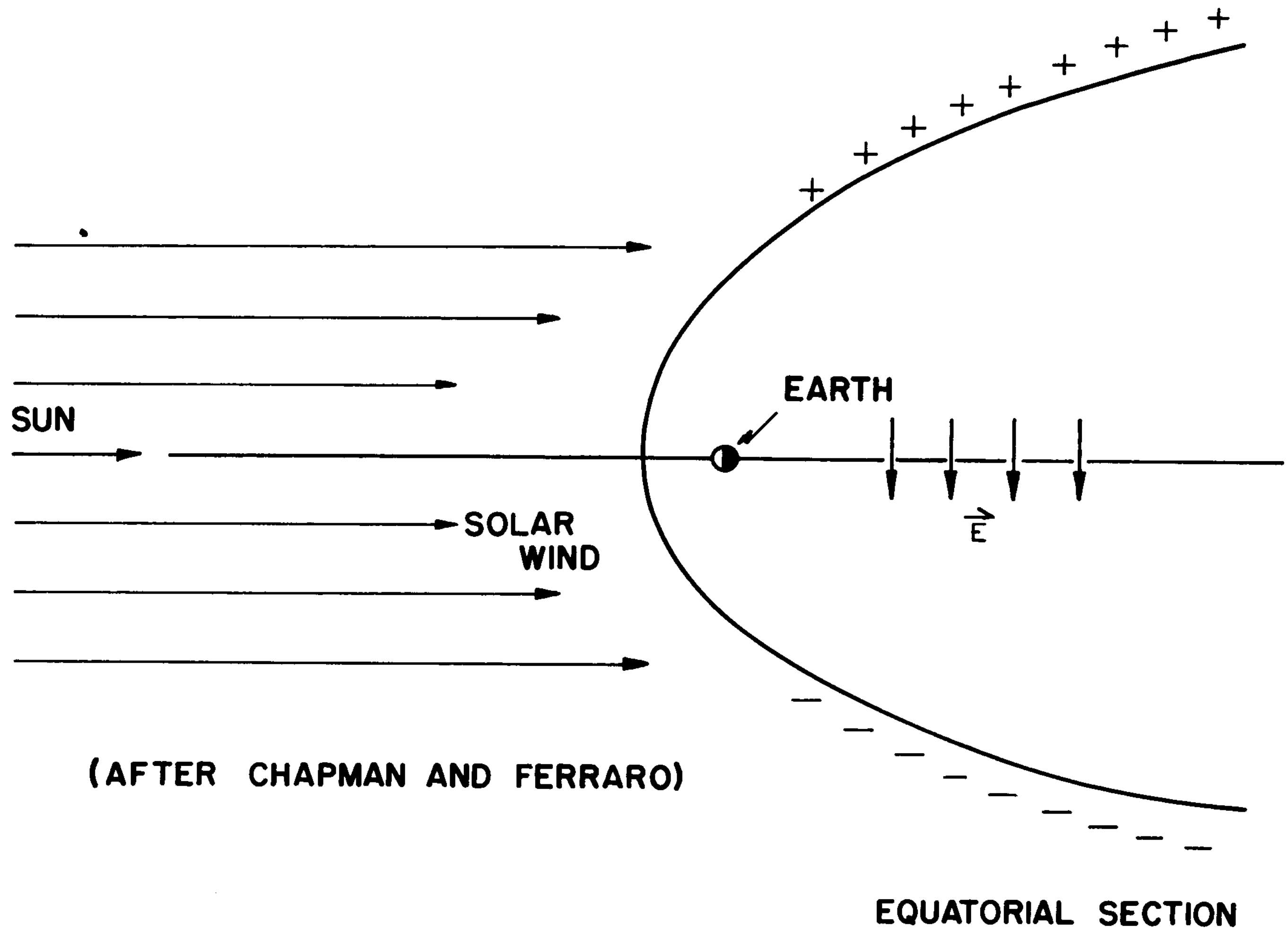
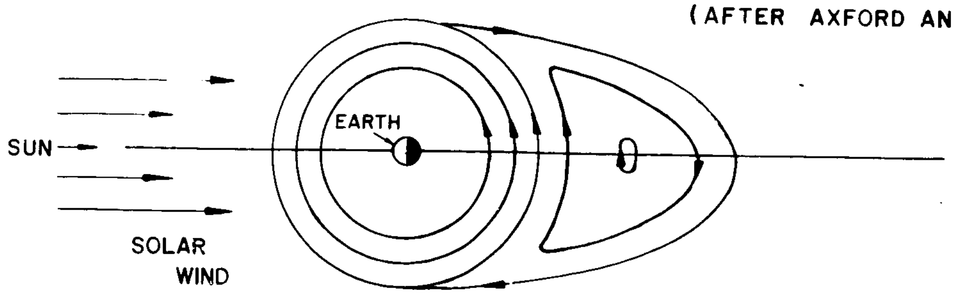



Figure 12

LAF-4-TTA




EQUATORIAL SECTIONS

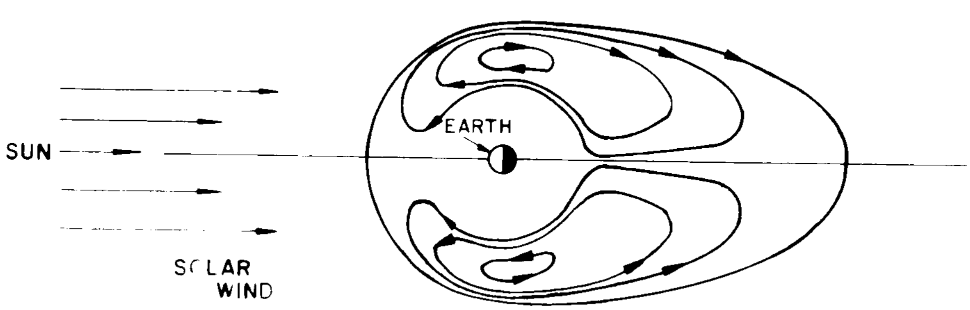



**Figure 13**

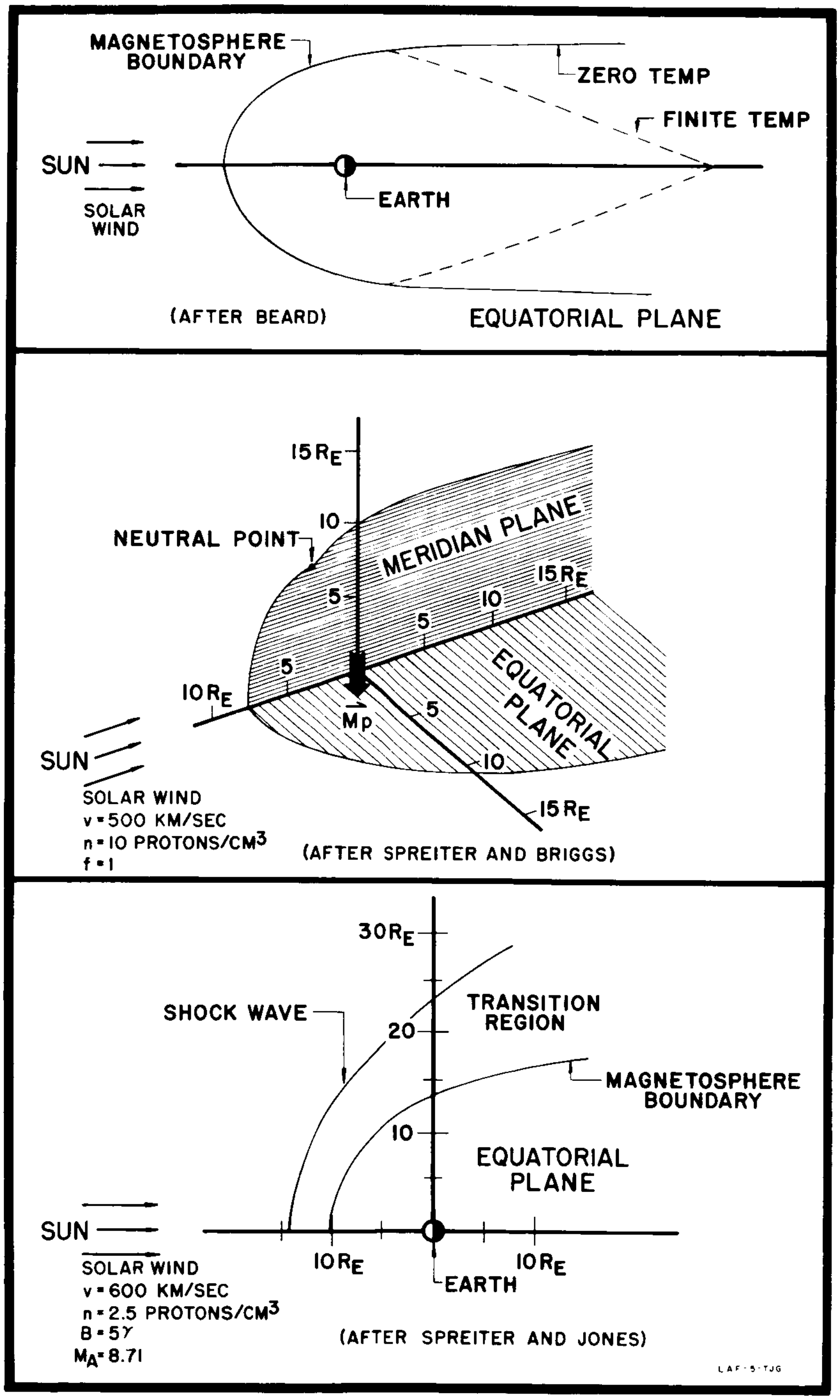
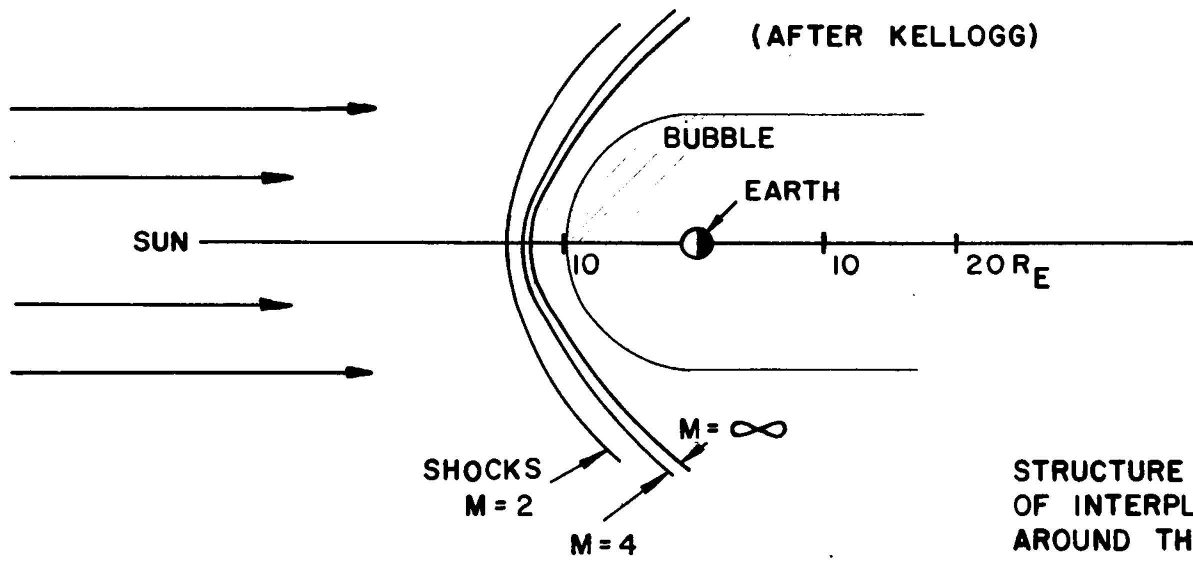

MAGNETOSPHERE BOUNDARY
ZERO TEMP
FINITE TEMP
SUN
SOLAR WIND
EARTH
(AFTER BEARD)
EQUATORIAL PLANE
15 $R_E$
10
NEUTRAL POINT
MERIDIAN PLANE
15 $R_E$
10
5
5
5
10 $R_E$
$\vec{M}_p$
5
EQUATORIAL PLANE
10
15 $R_E$
SUN
SOLAR WIND
v = 500 KM/SEC
n = 10 PROTONS/$CM^3$
f = 1
(AFTER SPREITER AND BRIGGS)
30 $R_E$
SHOCK WAVE
TRANSITION REGION
20
MAGNETOSPHERE BOUNDARY
10
EQUATORIAL PLANE
SUN
SOLAR WIND
v = 600 KM/SEC
n = 2.5 PROTONS/$CM^3$
B = 5γ
$M_A$ = 8.71
10 $R_E$
EARTH
10 $R_E$
(AFTER SPREITER AND JONES)
LAF-5-TJG

Figure 14




STRUCTURE OF THE FLOW OF INTERPLANETARY PLASMA AROUND THE EARTH FOR VARIOUS SUPERSONIC FLOW SPEEDS

Figure 15

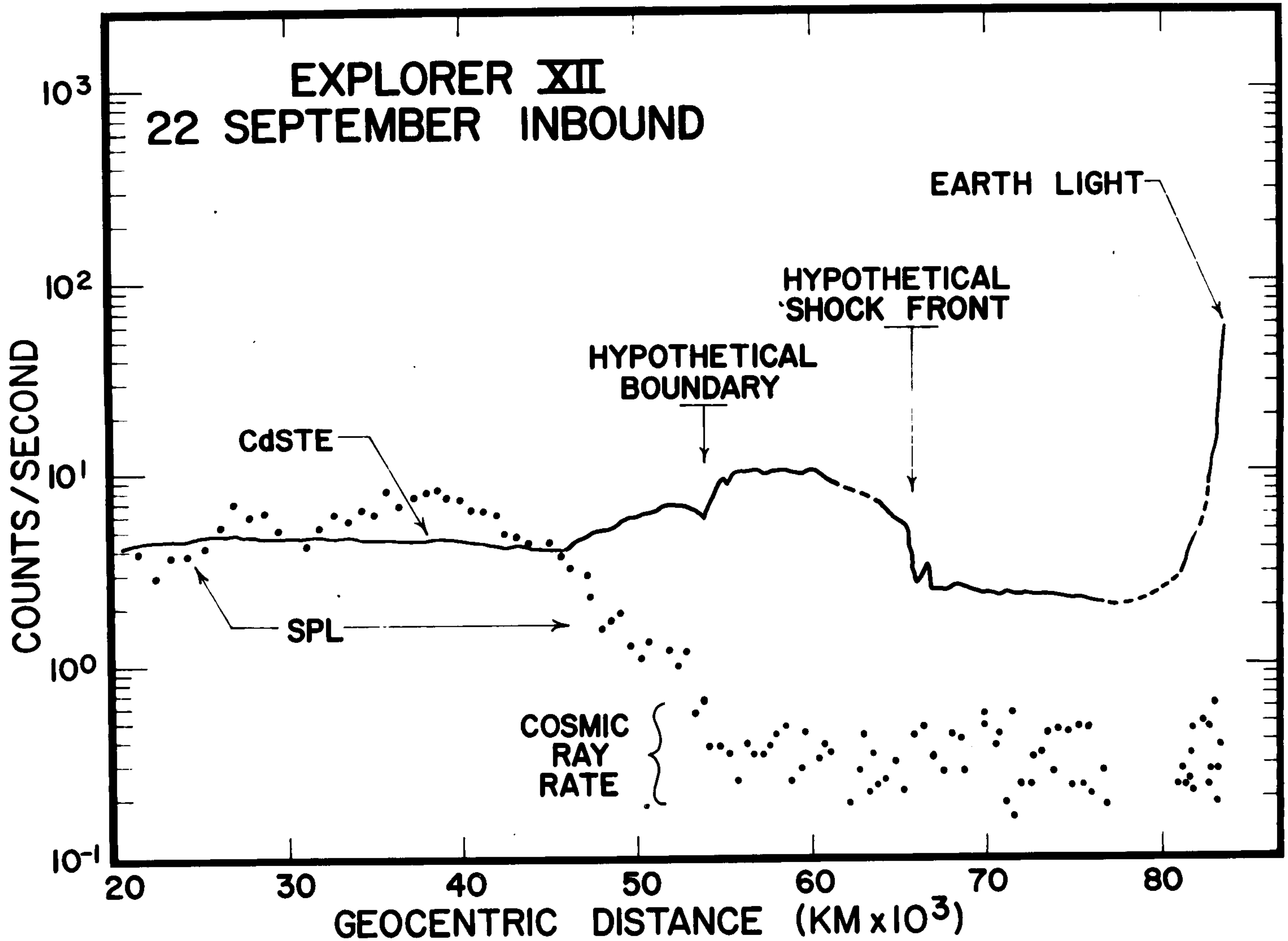

EXPLORER XII
22 SEPTEMBER INBOUND
EARTH LIGHT
HYPOTHETICAL SHOCK FRONT
HYPOTHETICAL BOUNDARY
CdSTE
SPL
COSMIC RAY RATE
COUNTS/SECOND
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
20
30
40
50
60
70
80
GEOCENTRIC DISTANCE (KM x $10^3$)

Figure 16

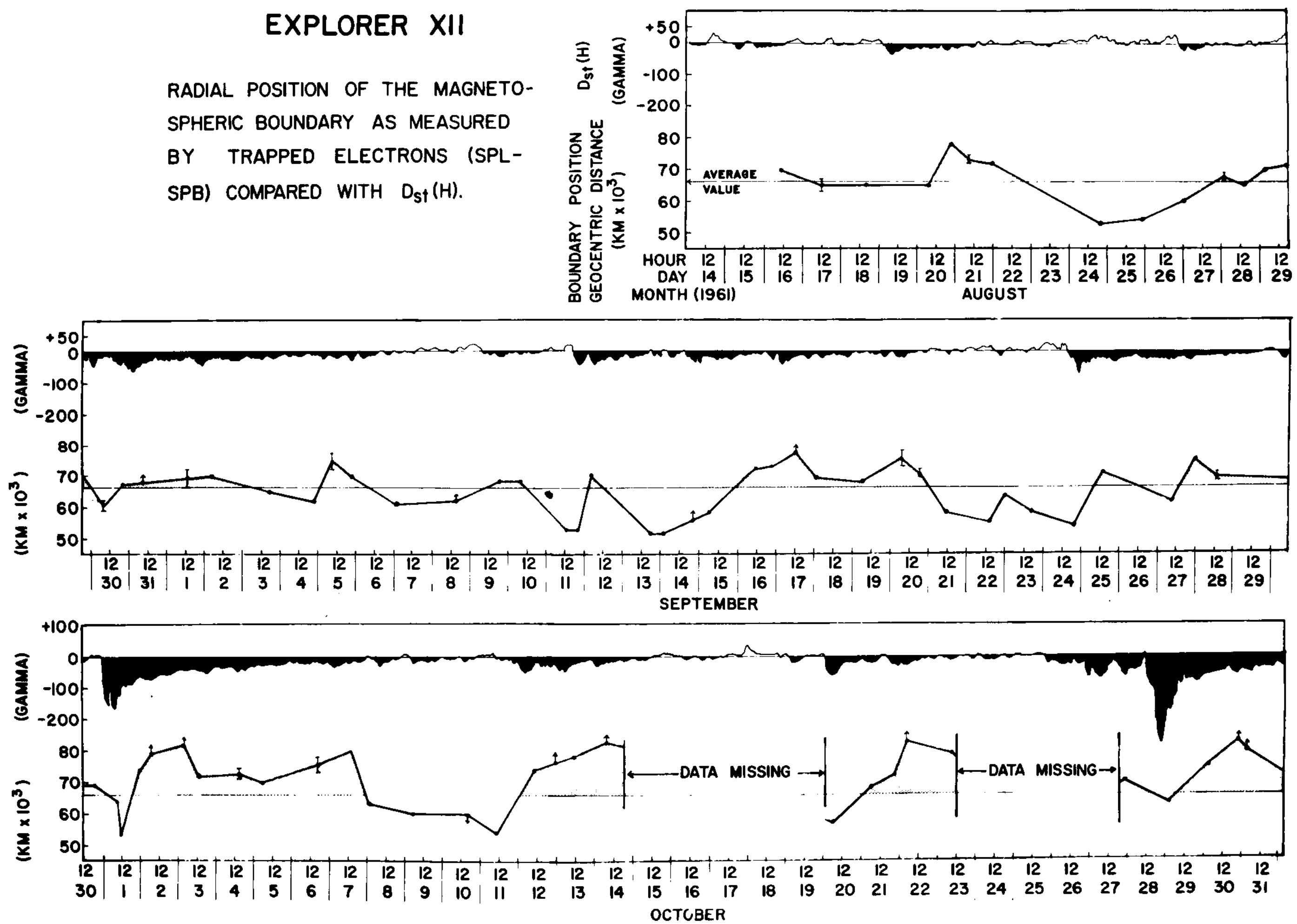

EXPLORER XII
RADIAL POSITION OF THE MAGNETOSPHERIC BOUNDARY AS MEASURED BY TRAPPED ELECTRONS (SPL-SPB) COMPARED WITH $D_{st}$(H).
$D_{st}$(H) (GAMMA)
BOUNDARY POSITION GEOCENTRIC DISTANCE (KM x $10^3$)
AVERAGE VALUE
HOUR
DAY
MONTH (1961)
AUGUST
SEPTEMBER
OCTOBER
DATA MISSING
DATA MISSING

Figure 17

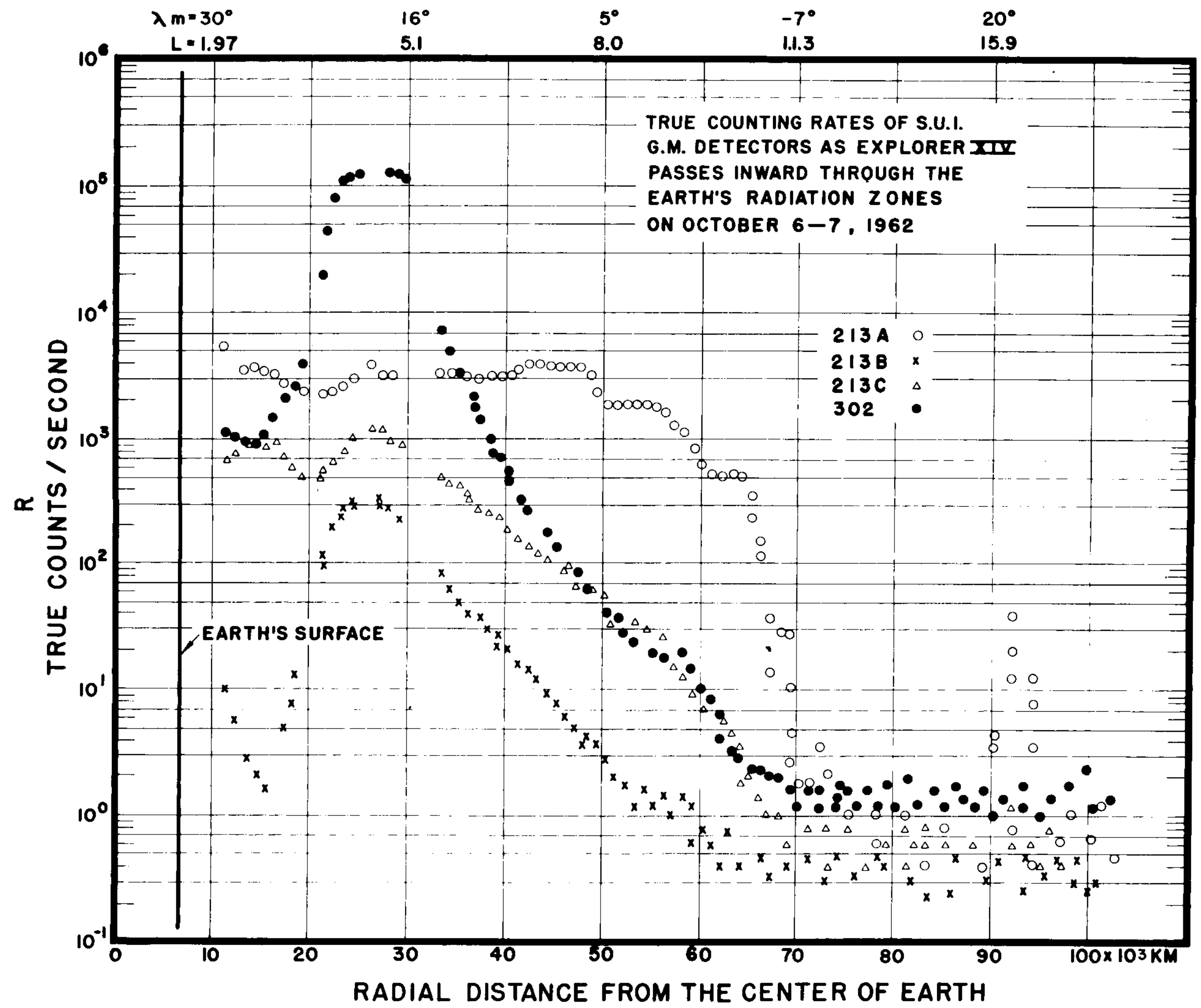

TRUE COUNTING RATES OF S.U.I.
G.M. DETECTORS AS EXPLORER XIV
PASSES INWARD THROUGH THE
EARTH'S RADIATION ZONES
ON OCTOBER 6—7, 1962
213A
213B
213C
302
λm=30°
L=1.97
16°
5.1
5°
8.0
-7°
11.3
20°
15.9
EARTH'S SURFACE
R
TRUE COUNTS / SECOND
RADIAL DISTANCE FROM THE CENTER OF EARTH
0
10
20
30
40
50
60
70
80
90
100x10³KM

Figure 18

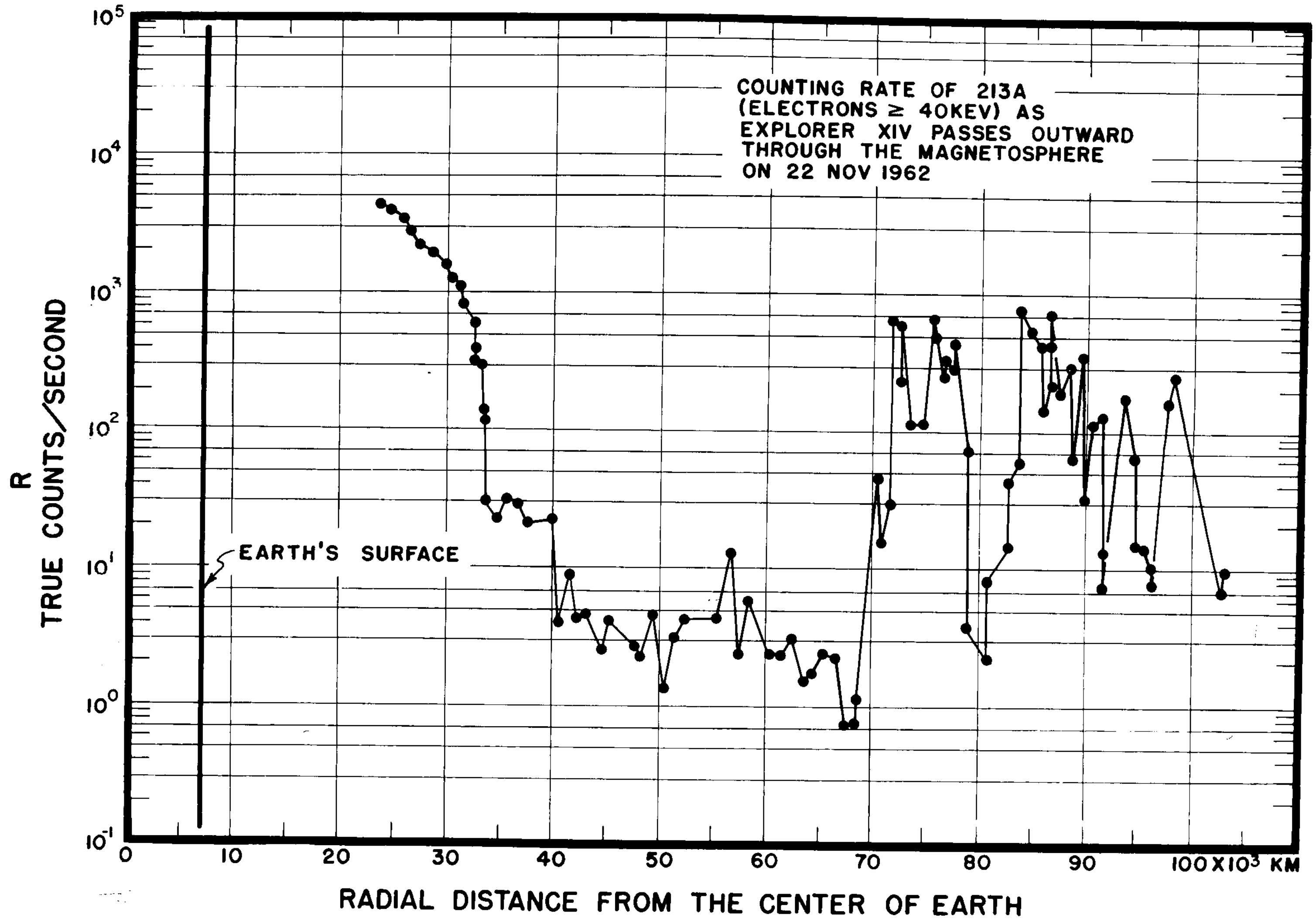

COUNTING RATE OF 213A
(ELECTRONS ≥ 40KEV) AS
EXPLORER XIV PASSES OUTWARD
THROUGH THE MAGNETOSPHERE
ON 22 NOV 1962
EARTH'S SURFACE
R
TRUE COUNTS/SECOND
$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
0
10
20
30
40
50
60
70
80
90
100 X $10^3$ KM
RADIAL DISTANCE FROM THE CENTER OF EARTH

Figure 19

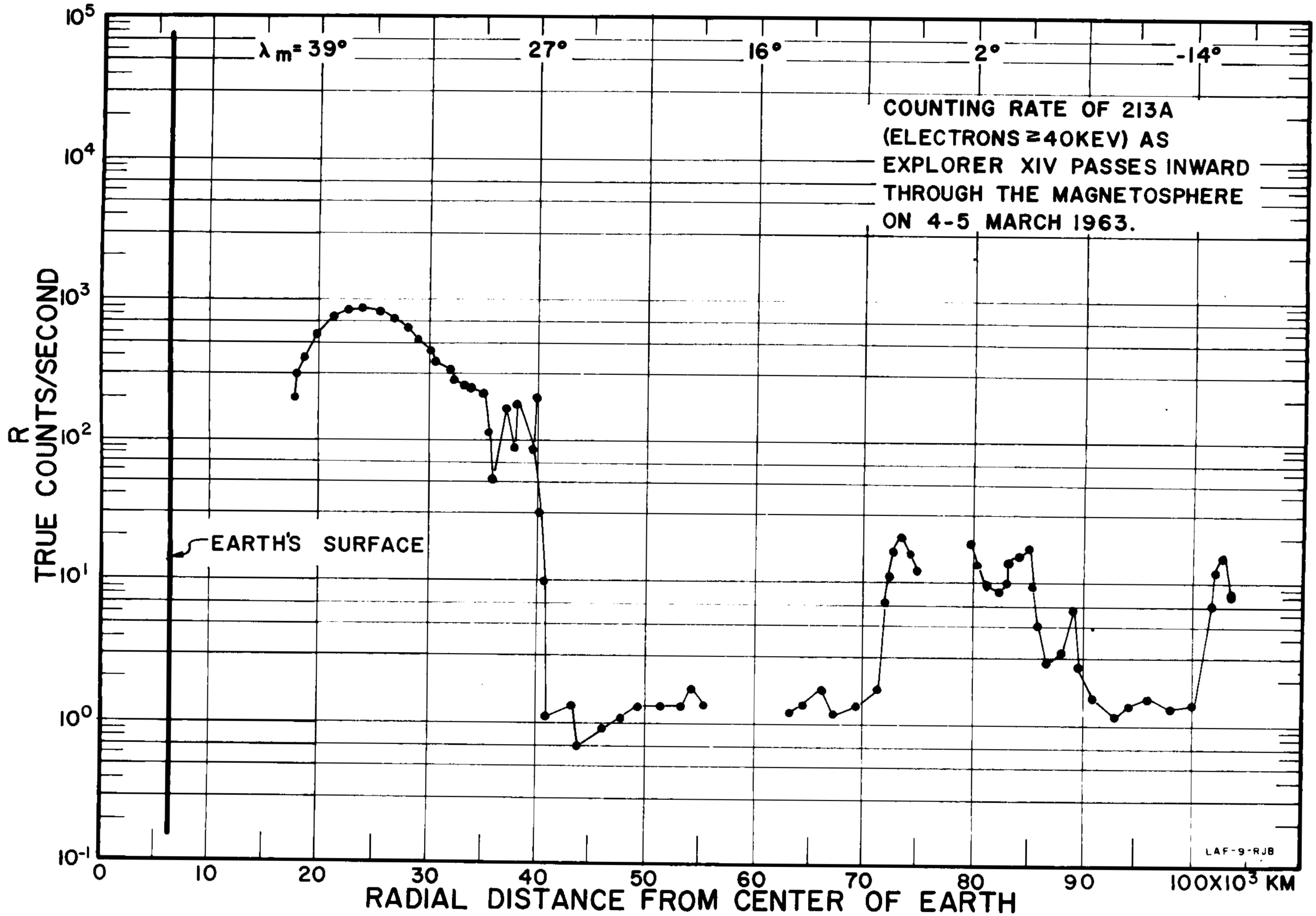
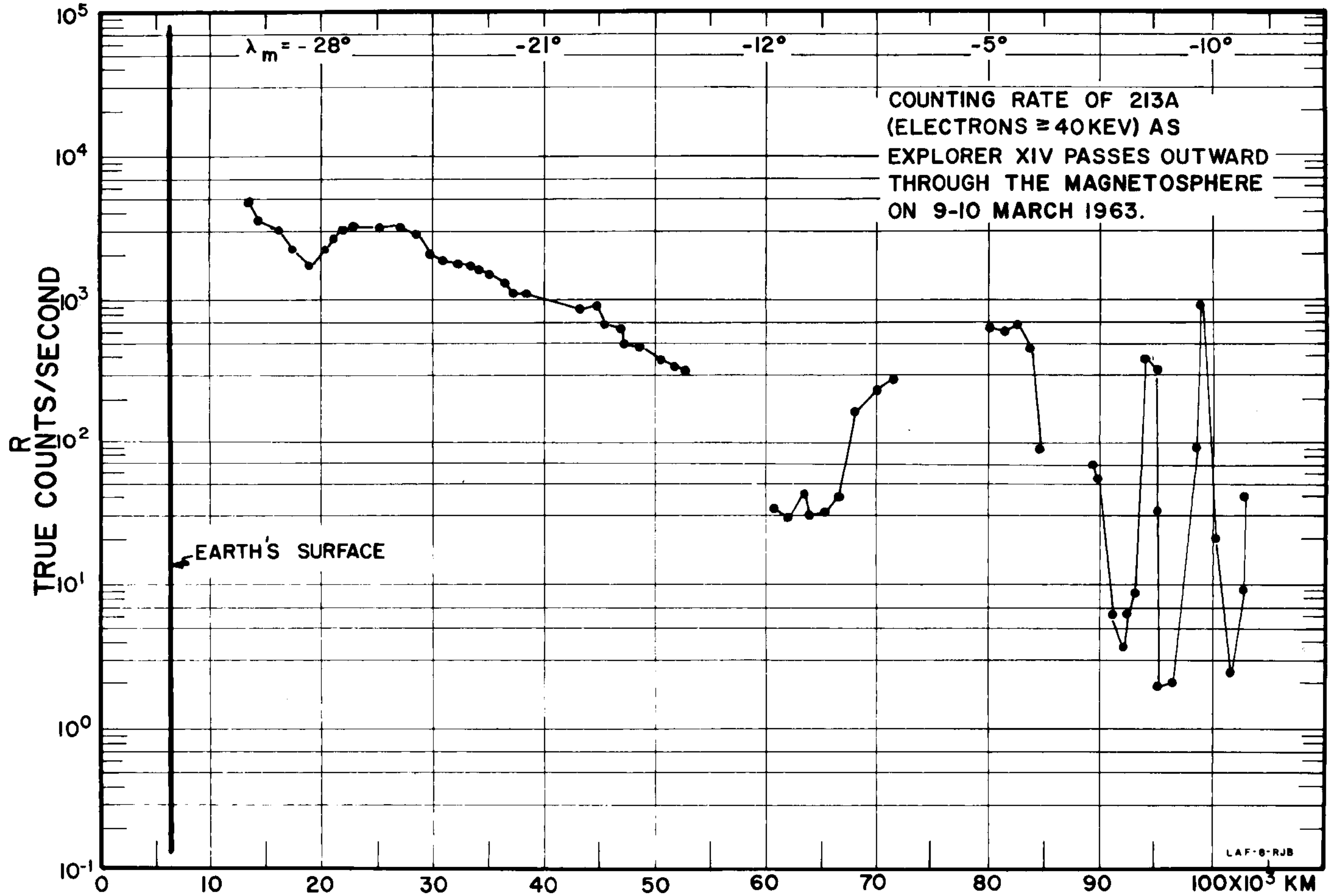

COUNTING RATE OF 213A
(ELECTRONS ≥40KEV) AS
EXPLORER XIV PASSES INWARD
THROUGH THE MAGNETOSPHERE
ON 4-5 MARCH 1963.
λ m= 39°
27°
16°
2°
-14°
EARTH'S SURFACE
R
TRUE COUNTS/SECOND
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
0
10
20
30
40
50
60
70
80
90
100X10^3 KM
RADIAL DISTANCE FROM CENTER OF EARTH
LAF-9-RJB

Figure 20



COUNTING RATE OF 213A
(ELECTRONS ≥ 40 KEV) AS
EXPLORER XIV PASSES OUTWARD
THROUGH THE MAGNETOSPHERE
ON 9-10 MARCH 1963.
$\lambda_m$ = -28°
-21°
-12°
-5°
-10°
EARTH'S SURFACE
TRUE COUNTS/SECOND
R
$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
0
10
20
30
40
50
60
70
80
90
100X10$^3$ KM
RADIAL DISTANCE FROM CENTER OF EARTH
LAF-6-RJB


Figure 21

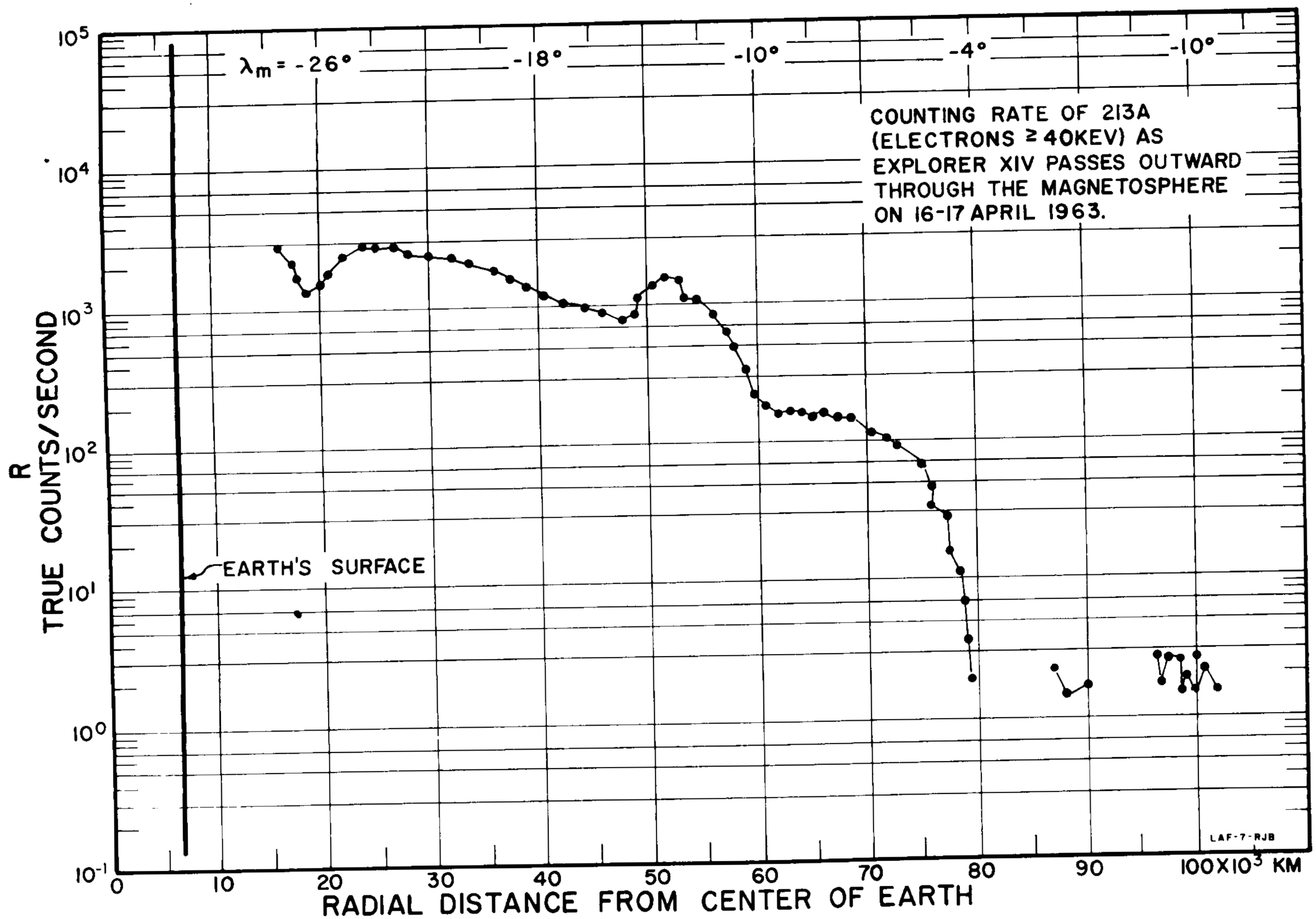

COUNTING RATE OF 213A
(ELECTRONS ≥ 40KEV) AS
EXPLORER XIV PASSES OUTWARD
THROUGH THE MAGNETOSPHERE
ON 16-17 APRIL 1963.
λm = -26°
-18°
-10°
-4°
-10°
EARTH'S SURFACE
R
TRUE COUNTS/SECOND
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
0
10
20
30
40
50
60
70
80
90
100X10^3 KM
RADIAL DISTANCE FROM CENTER OF EARTH
LAF-7-RJB

Figure 22